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Principles & Practices of Pond Aquaculture:

A State of the Art Review

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September 1983

Pond Dynamics/Aquaculture CRSP
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Prepared for the U.S. Agency for International Development as part of the Title XII Collaborative Research Support Program (CRSP) in Pond Dynamics/Aquaculture (Specific Support Grant No. AID/DSAN-G-0264).

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Cover design by Dena Gadomski.

CONTENTS

List of Tables ix

List of Figures xiii

Contributors xvii

Foreword xix
- Development of Aquaculture CRSP xix
- Preparation of State-of-the-Art Report xix
- Organization of State-of-the-Art Report xx
- Acknowledgements xx

PART 1 - COLLABORATIVE AQUACULTURE: AN OVERVIEW

History of International Aquaculture Development Activities by U.S. Government Agencies 3
Michael C. Cremer
- Foreword 3
- Foreign Aid Programs 3
- Aquaculture Development Assistance 3

History of United States Peace Corps Involvement in Freshwater Aquaculture 11
Gary L. Jensen
- List of Commonly Used Acronyms 11
- Introduction 11
- Country Information 12

PART 2 - PRINCIPLES OF POND AQUACULTURE

Biological Principles of Pond Culture: An Overview 21
William Y.B. Chang
- Introduction 21
- Pond Classification 21
- State of Knowledge 21
- Pond Dynamics 22

Biological Principles of Pond Culture: Bacteria and Nutrient Cycling 27
Russell Moll
- Nutrient Cycles 27
- Biological Filtration 29
- Nutrient Sources 29
- Bacteria as Food 29
- Pathogens 30
- Future Research 30
- Literature Cited 31

Biological Principles of Pond Culture: Sediment and Benthos 33
David White
Sediments and Nutrients 33
Sediment and Algal-Bacterial Relationship 34
Sediment and Macrobenthos Relationships 35
Benthic Invertebrates as a Food Source in Aquaculture 35
Summary 35
References 35

Biological Principles of Pond Culture: Phytoplankton and Macrophytes 39
C. Kwei Lin
Phytoplankton Communities and Species Composition in Fish Ponds 39
Productivity 40
Macrophytes and Benthic Algae 40
Research Needs 41
Literature Cited 41

Biological Principles of Pond Culture: Zooplankton 45
Marlene Evans
State of the Art of Zooplankton in Aquaculture Systems 45
Concluding Remarks 50
References 50

Biological Principles of Pond Culture: Fish 55
James Diana and David Ottey
Guidelines for Study 55
Results of the Literature Search 55
Ecological Perspective 59
Future Research Needs 62
References 62
Appendix A 65

A State of the Art Overview of Aquatic Fertility with Special Reference to Control Exerted by Chemical and Physical Factors 67
Darrell L. King and Donald L. Garling
Introduction 67
Basin Characteristics 68
Alkalinity 68
Nutrients 71
Other Buffers 73
Summary 74
Literature Cited 75

Fish/Plankton Interactions 77
Eugene Leslie Torrans
Introduction 77
Utilization of Plankton by Fish Larvae and Fry 77
Utilization of Plankton by Adult Fish 81

Fish/Plankton Interactions (continued)
Applied Aspects 83
Summary 84
Literature Cited 85

PART 3 - POND CULTURE PRACTICES

Pond Production Systems: Stocking Practices in Pond Fish Culture 91
Yung C. Shang
Foreword 91
Introduction 91
Factors Affecting the Stocking Rate of a Pond 91
Stocking Practices 92
Future Research Needs 99
References 99

Pond Production Systems: Fertilization Practices in Warmwater Fish Ponds 103
Randolph Yamada
Introduction 103
Inorganic Fertilizer 104
Organic Fertilizers 105
Pathway of Organic Fertilizers 105
Pond Soils 106
Application of Fertilizers 109
Integrated Agriculture-Aquaculture Farming 111
Future Research Needs 112
Literature Cited 112
Appendix A 115

Pond Production Systems: Feeds and Feeding Practices in Warmwater Fish Ponds 117
Randolph Yamada
Introduction 117
Finfish Nutritional Requirements 117
Feed Efficiency 121
Finfish Diets 132
Alternative Protein Sources for Fish Meal 137
Influence of Feed on Product Quality 137
Feeding Practices 138
Future Research Needs 142
Literature Cited 142

Pond Production Systems: Water Quality Management Practices 145
Arlo W. Fast
Introduction 145
Dissolved Oxygen (DO) 147
Temperature 152
Salinity 155
Alkalinity, Hardness, and pH 155

Pond Production Systems: Water Quality Management Practices (continued)
Dewatering and Drying 158
Turbidity 161
Domestic Wastes 161
Agricultural Pollution 161
Industrial Wastes 161
Aquatic Plants 161
Selected Future Research Needs 165
Literature Cited 165

Pond Production Systems: Diseases, Competitors, Pests, Predators, and Public Health Considerations 169
James A. Brock
Introduction 169
Infectious Diseases 169
Non-Infectious Diseases 174
Competitors, Pests and Predators 177
Prevention and Control Procedures for Competitors, Pests and Predators in Pond Aquaculture Systems 179
Public Health Considerations in Warmwater Pond Aquaculture 181
Recommendations for Future Programs 182
Literature Cited 182

Pond Culture Practices 187
John Colt
Overview 187
Effect of Growth Limiting Variables on Fish Production 189
Pond Engineering 191
References 194

PART 4 - MODELLING OF POND CULTURE SYSTEMS

Modeling the Hydromechanical and Water Quality Responses of Aquaculture Ponds - A Literature Review 201
Nikola Marjanovic and Gerald T. Orlob
Introduction 201
Summary 202
Annotated Literature Review 203
Conclusions 213
References 214

A Survey of the Mathematical Models Pertinent to Fish Production and Tropical Pond Aquaculture 225
David R. Bernard
Introduction 225
History of Predictive Models in Tropical Pond Aquaculture 226
Recommendations 229
Guidelines for Proposals 230

A Survey of Mathematical Models Pertinent to Fish Production and Tropical Pond Aquaculture (continued)

Literature Cited 231
Literature Summary 232
Index 232
Literature 233

PART 5 - POND AQUACULTURE: THE FUTURE

Pond Aquaculture: The Future 239
Summary 239
Planning Guidelines 239
Where Do We Go From Here? 240

TABLES

Table

PART 1 - COLLABORATIVE AQUACULTURE: AN OVERVIEW

History of International Aquaculture Development Activities by U.S. Government Agencies

1 Summary of SCC, TCA, FOA, ICA and AID Projects Providing Foreign Aid Assistance in Aquaculture Development 6

History of United States Peace Corps Involvement in Freshwater Aquaculture

No tables.

PART 2 - PRINCIPLES OF POND AQUACULTURE

Biological Principles of Pond Culture: An Overview

No tables.

Biological Principles of Pond Culture: Bacteria and Nutrient Cycling

No tables.

Biological Principles of Pond Culture: Sediment and Benthos

1 Examples of Benthic Algae and Macroinvertebrates Associated With Sediments in Aquaculture, Primarily Freshwater 34

Biological Principles of Pond Culture: Phytoplankton and Macrophytes

No tables.

Biological Principles of Pond Culture: Zooplankton

No tables.

Biological Principles of Pond Culture: Fish

1 List of Fish Species Commonly Cultivated in Tropical Ponds 56

2 Summary of Key Information Contained in All Aquaculture and Fish Biology Literature Examined for the Years 1976-78 for Fish Species Commonly Cultivated in Tropical Ponds 57

3 Summary of Key Information Contained in All Aquaculture and Fish Biology Literature Examined for the Years 1978-80 for Fish Species Commonly Cultivated in Tropical Ponds 58

4 Fish Population Interactions - Mechanisms of Density Effects on Growth 60

A State of the Art Overview of Aquatic Fertility with Special Reference to Control Exerted by Chemical and Physical Factors

1 Fish Cultured or Proposed for Culture Which Consume Forms of Blue-Green Algae 73

Table

Fish/Plankton Interactions

1 Zooplankton Standing Crop in Fish Ponds 77
2 First Food of Various Cultured and Non-Cultured Fish Species 79
3 Effect of Prey Density on Survival of Larval Fish 80
4 Age-Related Changes in the Food Habits of Five Species of Cultured Fish 81
5 Food Habits of Adult Planktivorous Fish 83

PART 3 - POND CULTURE PRACTICES

Pond Production Systems: Stocking Practices in Pond Fish Culture

1 Stocking Rate of Fry by Country and Species 93
2 A Typical Case of Multi-Stage Stocking of Milkfish Ponds of Different Size 94
3 A Typical Practice of Multiple-Size Stocking of Milkfish in Same Ponds in Taiwan 94
4 Stocking Rates in Monoculture Systems by Country and Species 95
5 Various Combinations of Species Used in Polyculture in China 97
6 Stocking Rate in Polyculture Systems in Selected Asian Countries, By Species 96
7 Stocking Combinations in Indonesia Pond 97
8 Stocking Combination Per Hectare Used In India and Pakistan 98
9 Stocking Combination Per Hectare Used In Israel 98
10 Example of Multi-Stage Polyculture in Taiwan 98
11 Example of Multi-Stage Polyculture in China 99

Pond Production Systems: Fertilization Practices in Warmwater Fish Ponds

1 Fish Production Increase with Fertilizaton Versus No Fertilization 103
2 Composition of Some Common Inorganic Fertilizer Materials 104
3 Average Composition of Several Manures 105
4 Summary of Pond Fertilization Experiments Using N, P, K Compared with Those Using P and K or P Only for Several Species of Fish 106
5 Soil Types and Textures 107
6 Liming Recommendations for Aquaculture Ponds 108
7 Total Fish Production in Ponds Given Various Levels of Lime and Chicken Manure Inputs Following Tilling and Repeated Leachings 109
8 "Lab-Lab" Fertilization Program 110
9 Annual Fish Production Data of Waste Utilization Projects 112
10 Advantages and Disadvantages of Organic Versus Inorganic Fertilization in Fish Ponds 115

Pond Production Systems: Feeds and Feeding Practices in Warmwater Fish Ponds

1 Gross Protein Levels for Certain Fish Species 118
2 Amino Acid Requirements of Certain Fish 119
3 Fatty Acid Patterns in Freshwater and Marine Fish 120
4 Changes in Fatty Acid Composition in Migrating Fish 121
5 Temperature Effect Upon Fatty Acid Composition 122
6 Vitamin Requirements for Fish 123
7 Mineral Requirements of Fish 124
8 Nutritional Composition of Some Feed Materials 125

Table

9	Food Conversion Ratio of Some Feed Materials	131
10a	Complete Diet Formulations	133
10b	Recommended Allowance for Vitamins in Supplemental and Complete Diets for Warmwater Fishes	134
11	Nutritional Value of Four Algae Groups	135
12	Nutritional Value of Certain Algae and Seaweeds	136
13	Amino Acid Profiles of Alternate Protein Sources	138
14	Growth on Fish Meal, Soybean Meal, and Algae Meal (SCP) Diets	139
15	Potential Alternate Protein Sources	141
16	Feeding Habits of Some Fish Species	141

Pond Production Systems: Water Quality Management Practices

1	Salinity, Temperature and Dissolved Oxygen Values for Selected Warmwater Pond Fishes	146
2	Solubility of Oxygen (mg/l) in Water at Different Temperature, Elevation and Salinities	149
3	Predicted Gains (+) and Losses (-) of Dissolved Oxygen from Fish Pond During the Night Based on Observed Oxygen Saturation at Dusk	150
4	Critical Secchi Disc Depths (in cm) for a 1-Meter Deep Fish Pond, as a Function of Water Temperature and Dissolved Oxygen Concentration at Dusk	151
5	Average Fish Production Rates, Average Fish Size, and Average Oxygen Concentrations in White Catfish Ponds Receiving Three Levels of Artificial Aeration	152
6	A Classification of Water Based on Salinity	156
7	Pond Productivity Related to Total Alkalinity	157
8	Estimated Lime Requirements in kg/ha Needed to Increase the Total Hardness and Alkalinity to 20 mg/l or Greater	158

Pond Production Systems: Diseases, Competitors, Pests, Predators, and Public Health Considerations

1	The Essential Vitamins and Deficiency Signs in Warmwater Fishes	175
2	Suggested Safe Levels for Some Pesticides for Aquatic Life	178

Pond Culture Practices

1	Potential Species for Pond Culture	189
2	Parameters of Interest in Pond Culture Systems	190
3	Factors Influencing the Optimum Pond Depth in Milkfish Ponds	193

PART 4 - MODELLING OF POND CULTURE SYSTEMS

Modeling the Hydromechanical and Water Quality Responses of Aquaculture Ponds - A Literature Review

No tables.

Table

A Survey of the Mathematical Models Pertinent to Fish Production and Tropical Pond Aquaculture

1 The Hierarchy of Empirical, Stock, and Mechanistic Models to Predict Fish Production From Tropical Ponds 226

PART 5 - POND AQUACULTURE: THE FUTURE

Pond Aquaculture: The Future

No tables.

FIGURES

Figure

PART 1 - COLLABORATIVE AQUACULTURE: AN OVERVIEW

History of International Aquaculture Development Activities by U.S. Government Agencies

No figures.

History of United States Peace Corps Involvement in Freshwater Aquaculture

No figures.

PART 2 - PRINCIPLES OF POND AQUACULTURE

Biological Principles of Pond Culture: An Overview

1 Low intensity tropical ponds 23

2 High intensity tropical ponds 23

3 Cool water tropical ponds 24

4 Brackish water ponds 24

Biological Principles of Pond Culture: Bacteria and Nutrient Cycling

No figures.

Biological Principles of Pond Culture: Sediment and Benthos

1 Pond manipulation for growth of benthic algae in milkfish (Chanos chanos) culture 34

Biological Principles of Pond Culture: Phytoplankton and Macrophytes

No figures.

Biological Principles of Pond Culture: Zooplankton

No figures.

Biological Principles of Pond Culture: Fish

No figures.

A State of the Art Overview of Aquatic Fertility with Special Reference to Control Exerted by Chemical and Physical Factors

1 Total inorganic carbon content and pH of freshwater at various carbonate-bicarbonate alkalinities at equilibrium with an atmospheric carbon dioxide level 340 ppm at 20 C 69

2 Carbon dioxide content of freshwater as a functon of pH and carbonate-bicarbonate alkalinity of the water 69

3 Amount of inorganic carbon which must be removed from various carbonate-bicarbonate alkalinities to reduce carbon dioxide from 100 to 10 percent saturation with an atmospheric carbon dixoide level of 340 ppm at 20 C given with the amount of phosphorus required for algal fixation of that carbon 70

Figure

Fish/Plankton Interactions

No figures.

PART 3 - POND CULTURE PRACTICES

Pond Production Systems: Stocking Practices in Pond Fish Culture

No figures.

Pond Production Systems: Fertilization Practices in Warmwater Fish Ponds

No figures.

Pond Production Systems: Feeds and Feeding Practices in Warmwater Fish Ponds

1 Factors affecting organoleptic qualities of fish 140

Pond Production Systems: Water Quality Management Practices

1 Characteristic dissolved oxygen cycle in a fish pond 147
2 Principal sources and sinks for dissolved oxygen in a fish pond 148
3 A method for predicting minimum dissolved oxygen during the night 152
4 A proposed technique for partial aeration of a fish pond 153
5 Growth rates of sockeye salmon as a function of water temperature and feeding rates 154
6 Thermal stratification in a fish pond 155
7 Oxygen depletion in a thermally stratified fish pond at Auburn, Alabama 156
8 Total hardness and total alkalinity in limed and un-limed fish ponds 159
9 Long term effects of liming on six Alabama ponds 160
10 Effects of copper sulfate and simazine of chlorophyll a concentrations in fish ponds 164
11 Effects of simazine on dissolved oxygen concentrations in fish ponds 164

Pond Production Systems: Diseases, Competitors, Pests, Predators, and Public Health Considerations

No figures.

Pond Culture Practices

No figures.

PART 4 - MODELLING OF POND CULTURE SYSTEMS

Modeling the Hydromechanical and Water Quality Responses of Aquaculture Ponds - A Literature Review

No figures.

A Survey of the Mathematical Models Pertinent to Fish Production and Tropical Pond Aquaculture

1 Schematic of a hypothetical empirical model with symbols according to Patten (1975) 227
2 Schematic of a hypothetical stock model 228

Figure

A Survey of the Mathematical Modesl Pertinent to Fish Production and Tropical Pond Aquaculture (continued)

3 Relative merits of three approaches to modeling production in tropical ponds 229

4 Schematic of a submodel of growth in a hypothetical mechanistic model 230

PART 5 - POND AQUACULTURE: THE FUTURE

Pond Aquaculture: The Future

No figures.

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FOREWORD

As a first step in initiating an Aquaculture CRSP (Collaborative Research Support Program), AID (Agency for International Development) contracted in 1977 with Resources Development Associates of Los Altos, California to complete a planning study for a fisheries and aquaculture CRSP. Resources Development Associates submitted the findings of its planning study to the JRC (Joint Research Council) in August, 1978. Among other priorities identified in this report, investigation of the principles and mechanisms of pond culture systems was recommended as an appropriate CRSP area with a high probability of increasing food fish production in the LDCs (less developed countries). In response to this recommendation, AID, through the BIFAD (Board for International Food and Agricultural Development), initiated further development of an aquaculture CRSP.

In February, 1980, the JRC announced its selection of Auburn University, CIFAD (Consortium for International Fisheries and Aquaculture Development), and the University of California in Davis to participate in this CRSP. CIFAD is composed of the University of Arkansas at Pine Bluff, the University of Hawaii, the University of Michigan, Michigan State University, and Oregon State University, which serves as the lead institution. At a meeting with AID and JRC representatives on February 22, 1980, it was recommended and later approved by the JRC that these institutions would participate in a tripartite management of the CRSP, and that CIFAD would be designated as the lead agency in the management of the program. At this same meeting the participants were instructed to prepare a preliminary proposal for the CRSP to be presented to the JRC at its meeting in June 1980.

The participating universities elected to develop a staged preliminary proposal providing a conceptual framework for the development and implementation of an aquaculture CRSP. The proposed first stage provided for completion of program development. Collaborative research was to be initiated in the second stage. Staging was considered necessary because the planning study accomplished by Resources Development Associates addressed the subject area of fisheries in its broadest sense, and thus did not provide adequate information for development and implementation of an aquaculture CRSP. Additionally, since the participating universities were asked to develop the preliminary proposal in the absence of funding, monies were not available to complete program development prior to award of the CRSP grant. Finally, time constraints were such that program development could not be completed to a point where collaborative research could begin immediately upon award of the CRSP grant.

The preliminary proposal was presented to and approved by the JRC on June 10, 1980. However, since the proposed program involved completion of program development as well as collaborative research activities, AID and the BIFAD elected to support the program development activities under a Title XII planning grant and to defer award of a CRSP grant until such time as the JRC had reviewed a detailed proposal of collaborative research activities identifying collaborative institutions and research plans. AID subsequently awarded a Specific Support Grant to Oregon State University as Management Entity for the Aquaculture CRSP.

DEVELOPMENT OF AQUACULTURE CRSP

The approach taken in the development of this CRSP was to accomplish a review and synthesis of the state-of-the-art knowledge of pond aquaculture and to undertake overseas site visits to determine research needs in the LDCs and to negotiate provisional administrative agreements with potential collaborating institutions. The findings from the state-of-the-art survey and the site visits were translated into planning guidelines to prepare the CRSP work plan and to develop a financial plan for the CRSP.

The role of the State-of-the-Art Survey in planning the CRSP has been noted above. However, it is anticipated that the Survey should play other vital roles in the total performance of the CRSP. In addition to its utility in planning, the Survey has served as a starting point in the development of detailed experimental plans. Therefore, it can potentially serve as a yardstick for gauging contributions which result from the CRSP activities. If these activities are productive, the body of knowledge encompassed in this Survey should become more comprehensive with time. Finally, researchers working in developing countries, including those employed by the CRSP and others interacting with CRSP activities, are frequently confronted with limited access to vitally needed information. The State-of-the-Art Survey is intended to provide, in a single volume, a comprehensive summary of contemporary information that can be made available to workers in remote locations. The extensive bibliography should be useful to these workers when requesting additional information from supporting agencies and institutions.

PREPARATION OF STATE-OF-THE-ART REPORT

To review and synthesize the state-of-the-art knowledge of pond aquaculture an interactive team of

specialists was selected from among the participating universities to assess the existing information on selected topic areas relating to pond culture systems. The authors and their affiliations are presented in the list of contributors. The primary question addressed in this synthesis is, "what is now known and, more importantly, what needs to be known?"

In the proposal, four aquaculture systems were considered to have the greatest potential for contributing to the supply of low cost animal protein in the LDCs. They are:

1. Small, low intensity tropical pond systems characterized by limited external inputs of feed or fertilizers.

2. Cooler water (15-25^{o}C) tropical ponds at medium to high elevations.

3. Brackish water and hypersaline ponds, including those in tropical mangrove zones.

4. Higher intensity tropical pond systems, characterized by high external inputs of feed or fertilizers.

ORGANIZATION OF STATE-OF-THE-ART REPORT

To present the information on pond culture practices in a useful manner this report has been organized into five parts:

- **Part 1 - Collaborative Aquaculture: An Overview**
- **Part 2 - Principles of Pond Aquaculture**
- **Part 3 - Pond Culture Practices**
- **Part 4 - Modelling of Pond Culture**
- **Part 5 - Pond Aquaculture: The Future**

A brief history of International Aquaculture Development activities by U.S. Government Agencies and a brief history of the U.S. Peace Corps involvement in freshwater aquaculture is presented in Part 1. The material on the history of the involvement of U.S. agencies in international aquaculture development is especially useful as there is no other single source where this historical material can be found. Further, this review helps to put the aquaculture CRSP in perspective with respect to other programs and activities of U.S. agencies.

The basic biological, chemical, and physical principles governing the operation of pond culture systems are examined in Part 2 in a series of eight papers. The principles of pond aquaculture are examined in an integrated analysis in the first six papers which were prepared by researchers at one institution. Chemical interactions are considered in the seventh paper. Another perspective on fish-plankton interactions is presented in the eighth and final paper in Part 2.

Pond culture practices including stocking, feeding, water quality practices and disease, competitors, pests, predators and public health considerations are addressed in Part 3 in a series of six papers. As in Part 2, pond culture practices are examined from two points of view in Part 3. The first five papers were prepared by researchers at one institution. Another perspective is presented in the last paper found in Part 3.

The modelling of aquaculture processes and systems is examined in Part 4. The modelling of pond culture systems is examined in two papers with respect to 1) hydromechanical and water quality responses of aquaculture systems and 2) a survey of the mathematical models pertinent to fish production and tropical pond aquaculture.

Finally, the state-of-the-art is assessed, and guidelines for the aquaculture CRSP are suggested in Part 5. It is important to note that one of the purposes in preparing this state-of-the-art report was to develop information that could be used in the formulating of an aquaculture CRSP that would meet the objectives of the Title XII legislation.

ACKNOWLEDGEMENTS

Many people have contributed to the development of this report. Their help is acknowledged gratefully. Without the individual authors who gave unselfishly of their time and expertise to the preparation of the papers, this report would not have been possible. Special thanks are due to Dinah Pfoutz who typed the tables. Finally we owe a debt of gratitude beyond measure to Robin Campbell who typed the manuscript. Her concern for clarity and detail is reflected throughout the text.

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PART 1

COLLABORATIVE AQUACULTURE: AN OVERVIEW

HISTORY OF INTERNATIONAL AQUACULTURE DEVELOPMENT ACTIVITIES BY U.S. GOVERNMENT AGENCIES

by

Michael C. Cremer

FOREWORD

Information pertaining to U.S. Government assistance to foreign nations for aquaculture development activities is widely scattered and difficult to obtain. Neither the Agency for International Development (AID) nor Peace Corps (PC), the largest technical assistance donor agencies, maintains a summary digest of project involvement in fisheries/aquaculture. AID/Washington has only recently expanded its Office of Development Information and Utilization (DIU) to respond to requests for technical and project experiential information and to summarize and maintain listings of development support activities. DIU's Development Information System, functioning as the AID "memory", is currently only 60% complete and dates back only to September 1974 with respect to project descriptions, evaluations and other program documents. Available information prior to 1974 must be manually retrieved from the DIU Development Information Centers in the State Department buildings in Washington, D.C., and Rosslyn, Virginia. PC to date has no central development information system. All available information pertaining to fisheries must be manually retrieved from files and/or obtained verbally from PC personnel. Considering these limitations in reporting systems, the following history of international aquaculture development activities by U.S. Government agencies may not be complete.

FOREIGN AID PROGRAMS

The United States foreign aid program for developmental assistance was initiated in 1938 with the creation of the International Committee on Scientific and Cultural Cooperation (SCC). A relatively small program at its inception, SCC formed the foundation for major U.S. foreign aid programs during and after World War II, including the Lend-Lease program and the Marshall Plan. These programs were followed in 1949 by President Truman's "Point Four" program of technical assistance to less developed nations. Approved as PL 535 in June 1950, Truman's program became the Technical Cooperation Administration (TCA), the forerunner of today's Agency for International Development. In 1954, the TCA merged with the Mutual Security Act (MSA) of 1953 to form the Foreign Operations Administration (FOA). This program was modified the following year into the International Cooperation Administration (ICA) and placed within the State Department by President Eisenhower. Seven years later, the program was again reorganized, and through the Foreign Assistance Act of 1961, the U.S. Agency for International Development (AID) was created. Initially designed to administer all U.S. foreign aid, AID was modified to 1967 to exclude military and economic aid, placing AID's emphasis on international development assistance. Today, the AID program administers foreign aid resources to developing nations for food production, nutrition, family planning, health care, education, technical assistance, school and hospital support, international program development, disaster relief and regional development.

Numerous other foreign assistance programs are administered by the U.S. government in addition to AID. Under separate legislation, U.S. aid is also provided to foreign nations under the Food for Peace (PL 480) program, the National Oceanic and Atmospheric Administration (NOAA), ACTION (Peace Corps), multilateral institution support programs (World Bank, Inter-American Development Bank, etc.), and private U.S. programs, many of which are coordinated by AID, its respective missions and other government institutions.

AQUACULTURE DEVELOPMENT ASSISTANCE

Scientific and Cultural Cooperation (SCC) Program

One of the earliest development efforts in freshwater fisheries/aquaculture by the U.S. Government was the Technical Assistance in Agriculture project in Mexico from 1942 to 1950. Encompassing rubber development, fisheries and general agriculture, the project was effected in 1942 by an exchange of notes between the United States and Mexican governments. Under the fisheries portion of the project, one marine and one freshwater biologist from the Fish and Wildlife Service of the Department of the Interior provided technical assistance during the periods 1942-1950 and 1942-1947, respectively. The freshwater fisheries subproject was designed to assist in improving the food and recreational resources of the interior fisheries of Mexico, and dealt only secondarily with aquaculture through hatchery support and stocking programs.

Technical Cooperation Administration (TCA), Foreign Operations Administration (FOA), and International Cooperation Administration (ICA) Programs

Aquaculture development efforts were expanded in the 1950's through the Technical Cooperation Administration, Foreign Operations Administration and International Cooperation Administration programs. Numerous short-term studies were conducted through various U.S.-based government agencies and the network of U.S. Overseas Missions (USOM). Examples include a Report on Fisheries in Cambodia, conducted through USOM/Cambodia, and the Project for Inland Fisheries Development in Nepal, conducted by the U.S. Agriculture Cooperative Service in cooperation with the Nepal-American Small Industries Development Cooperative Services.

On a broader scale, several long-term projects dealing with aquaculture were conducted under the TCA, FOA, and ICA foreign aid programs. In 1950, the U.S. Commission for Economic Development (USCED) initiated a long-term joint Liberian-USCED cooperative program in agriculture, forestry and fisheries. Funded from 1951 through 1967, the project provided technical assistance in fish propagation and pond construction for freshwater fisheries. From 1951 to 1953, the Institute of Inter-American Affairs, Division of Agriculture and Natural Resources, provided inland fisheries/fish culture technical service to the Government of El Salvador. Between 1956 and 1962, the ICA sponsored a fisheries development project in Korea that included 2 years of technical assistance to expand facilities to culture freshwater fish as a means of supplementing the marine catch and income of rural communities. Five other fisheries development/conservation projects were also active during this period under ICA guidance: (1) joint RKG-USOM/Cambodia Fishery Conservation Project with 4 years of fish culture technical assistance (1958-1962); (2) joint USOM-Dominican Republic fishery conservation project to support largemouth bass and tilapia introductions, conduct trout surveys, upgrade fish culture experiment stations, and recommend stocking programs (approx. 1955-1960); (3) U.S. Technical Cooperative Mission to India Project to develop a fisheries extension service in India for training fish farmers and fishermen in the latest methods of fish culture and capture fisheries (1957-1959); (4) ICA Pakistan Fisheries Development Project involving commodity assistance (160 ton exploratory boat), fish boat mechanization, use of synthetic net twines, refrigerated fish markets, mechanized fish dryers and fishpond weed control (1953-1962); and (5) ICA Bolivia Fish Culture Project to conduct trout culture studies and to introduce and conduct culture trials with tilapia.

Agency for International Development (AID) Program

U.S. foreign aid for aquaculture development was expanded in the 1960's under the U.S. Agency for International Development. Long-term projects initiated by the TCA and ICA in Liberia, Pakistan, Cambodia, Korea, Vietnam and Thailand were continued under the AID program (Table 1). Short-term technical assistance was increased, and nine new long-term technical assistance projects were initiated by AID between 1962 and 1969 (Table 1). New long-term projects continued to be concentrated in the Asia region, with new AID-initiated projects in Indonesia, Korea, Laos, East Pakistan and Thailand; as well as an Asia Regional development project. Only two projects were initiated by AID during this period outside of the Asia region: Brazil and Nigeria.

AID also greatly expanded its U.S.-based technical capabilities in fisheries and aquaculture during the 1960's through collaborative assistance programs with U.S. universities. In 1966, AID requested Auburn University (AU), Auburn, Alabama, to provide technical assistance in establishing a worldwide inland fisheries and aquaculture program. The objectives of the program, initiated in 1967, were first to conduct surveys to determine the fish culture potential of selected developing countries, and then to provide supervised construction of research facilities, in-country technical assistance, and training of fishery scientists from participating developing countries. The program was modified in 1969 and structured under a Basic Ordering Agreement to provide continued short-term technical assistance as well as long-term project development assistance through specific country task orders with AU.

In 1969 and 1970, AID further expanded its collaborative assistance programs with U.S. universities by providing institutional development grants to the University of Rhode Island (URI) and AU. Authorized under Section 211(d) of the Foreign Assistance Act of 1961, these grants provided funds to strengthen university capacities to develop and carry out programs concerned with economic and social development of less developed countries (LDC's). Grant support was used at URI to establish the International Center for Marine Resource Development (ICMRD) to strengthen its research, consultation, and service capacities in marine resources, with emphasis on fisheries (including mariculture). At AU, the International Center for Aquaculture (ICA/AU) was established with grant support to strengthen Auburn's specialized competency in aquaculture and to expand its capability in international development activities in inland fisheries and aquaculture.

AID continued expansion of its program in aquaculture development assistance in the 1970's. In Africa, AID combined resources with the PC to provide long-term assistance in fish culture to the Central African Republic, Zaire and Cameroon (Table 1). In Asia, on-going projects in Vietnam, Korea, Laos, East Pakistan, Thailand and the Asia Region were continued (Table 1). Six new long-term projects dealing specifically with aquaculture, and three new long-term projects with minor components in aquaculture were added to AID programs in the Philippines, Indonesia and Thailand (Table 1). In Latin America, the Brazil aquaculture development project was extended, and thirteen new long-term projects emphasizing or including aquaculture activities were implemented in Panama (2), El Salvador (1), Honduras (2), Chile (2), Colombia (1), Jamaica (2), Peru (2) and the Eastern Caribbean Region (1). In Europe, the Institute of Azores in Portugal received AID assistance from 1977 to 1979.

AID also continued its collaborative assistance program in aquaculture with AU throughout the 1970's. With increased demand for short- and long-term technical assistance from USAID missions worldwide, ICA/AU advisory services were increasingly utilized under a series of University Services, Technology Transfer, and Strengthening grants. ICA/AU services

were also utilized for 10 of 12 AID long-term projects requiring overseas technical advisors during this period. Between 1970 and 1979, AID utilized 3,410 person-days of short-term technical services overseas and 54 person-years of long-term technical services overseas from the ICA/AU.

AID funding was also provided for specialized programs during the 1970's. In 1975, a cooperative agreement between AID and NOAA provided program support to AID's Development Support Bureau's (DSB) Agriculture/Fisheries Division. Between 1975 and 1979, AID provided funding to the Oceanic Institute in Hawaii to support research on the artificial propagation of milkfish. Since 1979, AID has provided funding to the International Center for Living Aquatic Resources Management (ICLARM) for support in improving productivity in the fishery sectors of LDC's. Support was also given to the University of California/Davis in 1979 for research to study developmental problems occurring in hatcheries with larval marine fish.

AID has continued its development assistance efforts in the field of aquaculture in the early 1980's. Eighteen long-term assistance projects emphasizing or including aquaculture are currently active under AID programs in Africa, Asia and Latin America (Table 1). An additional seven major aquaculture projects have been proposed for implementation in FY 1981-82 (Table 1). AID's DSB has maintained its collaborative program with NOAA, utilizing the full-time services of two National Marine Fisheries Service (NMFS) employees in the AID/Washington center. The DSB of AID has also continued its collaborative services program with the ICA/AU, having utilized 522 person-days of short-term advisory services and 4.25 person-years of long-term advisory services between January 1980 and May 1981. Funding has also continued for the ICLARM program. More recently, AID has implemented a program for Fisheries and Aquaculture Collaborative Research in the Developing Countries. Under Title XII legislation, this program will utilize the collaborative services of the ICA/AU, the University of California/Davis, and the Oregon State University and affiliated universities consortium to conduct research support programs emphasizing needs and priorities in developing countries.

National Oceanic and Atmospheric Administration Program

The National Oceanic and Atmospheric Administration was created in 1970 to improve understanding, management and conservation of marine and atmospheric resources in the U.S. Some components of NOAA are among the oldest in the federal government. NOAA's National Ocean Survey traces its origins to the Survey of the Coast in 1807, and NOAA's National Marine Fisheries Service was formed in 1871 as the Office of the Commissioner of Fish and Fisheries. Today, NOAA is a major federal agency, with more than 15,000 employees comprising 38% of the Department of Commerce workforce.

International fisheries involvement, particularly as it relates to aquaculture, is centered in NOAA's fisheries (NMFS) and research and development (Sea Grant) programs. The NMFS provides most of NOAA's international development support for aquaculture through its Office of International Fisheries Affairs. This office provides liaison for U.S.-overseas development interests, reports foreign statistical data on fisheries, publishes a monthly newsletter on developments in world fisheries, provides for scientific exchange and training, and maintains regional Fishery Attache positions in Mexico and Japan. The NMFS currently has programs with France (CENEXO), the People's Republic of China (YSFRI), and Japan (UJNR) that provide funding for aquaculture scientist exchanges and information dissemination. Between 1962 and 1978, NMFS provided training in the U.S. for 34 foreign fisheries personnel, six of which were trained in aquacultural techniques. NMFS also maintains a Committee on Fisheries Investigations which provides input on aquaculture development to developing countries through the United Nations Food and Agriculture Organization (FAO). Most recently, NMFS has been requested by AID to provide technical assistance and logistic support for a multi-faceted aquaculture development project in Indonesia.

NOAA also provides international development assistance through its Sea Grant International Program (SGIP). SGIP was established within the National Sea Grant College Program in 1976 as the International Cooperation Assistance Program. The program was amended in 1978 and the name changed to SGIP. The goals of the SGIP are to enhance the research and development capability of developing foreign nations with respect to ocean and coastal resources, and to promote the exchange among the U.S. and foreign nations of information and data with respect to the assessment, development, utilization and conservation of such resources. To date, twelve projects have been supported by SGIP. One of these, the URI-Malaysian University Project, has provided assistance in aquaculture as well as marine resources development. Project emphasis has been on improving fisheries economics capabilities within Malaysia. An international symposium on mangrove ecosystems was also funded under this project to provide information useful to both marine fishery managers and coastal aquaculturists.

Table 1

SUMMARY OF SCC, TCA, FOA, ICA AND AID PROJECTS PROVIDING FOREIGN AID ASSISTANCE IN AQUACULTURE DEVELOPMENT

Region/Country	Project Title	Initial Implementing Agency	Project Emphasis	Project Duration
AFRICA				
Liberia	Cooperative Program in Agriculture, Forestry and Fisheries	TCA	Fish propagation, pond construction	1951-'67
Nigeria	Fisheries Development	AID	Fish breeding, fish culture, pond construction	1962-'69
Central Africa Republic	Inland Fish Culture Extension	AID/Peace Corps	Fish culture, extension	1977-present
Zaire	Fish Culture Expansion	AID	Fish culture, pond construction	1978-present
Sierra Leone	Improved Rural Technology	AID/Peace Corps	Fish culture, extension	1979-present
Senegal	Lowland and Fish Culture	AID/Peace Corps	Fish culture, extension	1980-present
Cameroon	Small Farmer Fish Production	AID/Peace Corps	Pond construction/ renovation, fish culture, extension	1980-present
Egypt	Aquaculture Development	AID	Fish culture, research, demonstration, extension	1980-present
Mali	Mali-San Pilot Fisheries Production	AID/Peace Corps	Fish breeding fish culture	1981-present
Rwanda	Fish culture	AID/Peace Corps	Pond construction, fish culture, extension	Proposed
Burundi	Highland Fisheries Development	AID	Fish culture, training	Proposed
Lesotho	Thaba Bosiu Rural Development	AID	Aquaculture sub-project assistance	Proposed
ASIA				
Pakistan	Fisheries Development	ICA	Minor assistance in fishpond weed control	1955-'62
Korea	Fisheries Development	ICA	Freshwater fish culture	1956-'64
India	Fisheries Development	ICA	Inland fisheries extension	1957-'59
Cambodia	Fisheries Development	ICA	Freshwater fish culture	1958-'63
Vietnam	Fisheries	ICA	Hatchery development, fish culture, training, extension	1958-'75

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Table 1 (Continued from previous page)

Region/Country	Project Title	Initial Implementing Agency	Project Emphasis	Project Duration
Thailand	Agriculture Development	ICA component	Pond fish culture	1962-'66
Indonesia	University Development	AID	University development and training, including fish culture component at IPB/Bogor	1962-'66
Korea	Rural Policy Plan Survey	AID	Fish hatchery operation	1963-'74
Laos	Agriculture Development	AID	Hatchery improvement, fingerling production, extension	1965-'74
East Pakistan	Consultant Services to the East Pakistan Agricultural University at Mymensingh	AID	University development, fisheries	1967-'70
Thailand	Fisheries Development	AID	Aquaculture training	1967-'73
Thailand	Applied Agriculture Research in Northeast	AID	Minor component for rice-fish culture and cage culture of fish	1968-'71
Asia Regional	Southeast Asia Fisheries Development Center	AID	Aquaculture research	1969-'73
Philippines	Inland Fisheries	AID	Brackish- and fresh-water aquaculture research and training	1970-'74
Philippines	Bicol River Basin Development Program	AID	Minor component-fisheries survey	1973-'79
Philippines	Aquaculture Production	AID	Brackish- and fresh-water aquaculture research and extension	1974-'78
Indonesia	Brackish Water Fishery Production	AID	Brackish water aquaculture, extension, training	1976-'81
Thailand	Lam Nam Oon On-Farm Development	AID	Fish propagation, community fishponds	1977-present
Philippines	Freshwater Fisheries Development	AID	Fish seedling production, extension	1978-present
Indonesia	Provincial Development I	AID	Minor assistance to aquaculture facilities in Sumatra	1978-present
Indonesia	Provincial Development II	AID	Minor assistance to aquaculture facilities & research in Kalimantan	1979-present
Thailand	Village Fish Pond Development I	AID	Community fishponds	1979-present

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Table 1 (Continued from previous page)

Region/Country	Project Title	Initial Implementing Agency	Project Emphasis	Project Duration
Indonesia	Small Scale Fisheries Development	AID	Multi-faceted aquaculture, artisanal fisheries; 6 sub-projects	Proposed 1981
Thailand	Village Fish Pond Development II	AID	Community fishponds, extension service upgrading	Proposed 1981
Indonesia	Applied Agriculture Research	AID	Aquaculture research subproject	Proposed 1982
EUROPE				
Portugal	Technical Consultants and Training, Institute of Azores	AID	Minor component seaweed culture	1977-'79
LATIN AMERICA				
Mexico	Technical Assistance in Agriculture	SCC	Fish hatchery and stocking programs	1942-'50
El Salvador	Inland Fisheries/ Fish Culture	TCA	Inland fisheries, aquaculture	1951-'53
Bolivia	Fish Culture	ICA	Trout and Tilapia culture	1955-'58
Dominican Republic	Fishery Conservation	ICA	Inland fisheries management and aquaculture	1955-'60
Brazil	Fish Production, Processing and Marketing	AID	Reservoir management, fish culture research and extension	1966-'78
Panama	Panama Aquaculture	AID	Aquaculture research	1971-'73
El Salvador	Inland Fisheries	AID	Inland fisheries management, aquaculture research and extension	1972-'76
Honduras	Core Services Rural Development	AID	Included component for rural fish farming	1972-'79
Chile	Agricultural Development Fund	AID	Project component for fish marketing cooperative development (trout farming included)	1975-'80
Chile	Rural Cooperative Upgrading	AID	Training, cooperative development (trout farming included)	1977-'79
Colombia	Fisheries Research	AID	Aquaculture research and facility development	1977-'80
Honduras	Nutrition	AID	Aquaculture subproject for hatchery development, aquaculture extension	1977-'79

Continued next page

Table 1 (Continued from previous page)

Region/Country	Project Title	Initial Implementing Agency	Project Emphasis	Project Duration
Jamaica	Inland Fisheries Development	AID	Fish seedling production, aquaculture extension, training	1977-'79
Peru	Freshwater Fisheries Development	AID	Trout hatchery and feed mill development, community trout ponds	1977-'80
Eastern Carribean Regional	Carribean Development Facility	AID	Multi-faceted loan program, including credit for fisheries/ aquaculture	1978-present
Panama	Guaymi Area Development	AID	Community integrated fish/animal husbandry ponds	1979-present
Peru	Rural Enterprises II	AID	Credit for small entrepreneurs, including trout farmers	1979-present
Jamaica	Fish Production System Development	AID	Aquaculture production, extension-Peace Corps assistance	1980-present
Panama	Rural Aquaculture Development	AID	Aquaculture production and extension	1981-present
Dominican Republic	Inland Fisheries	AID	Aquaculture and inland fisheries development	Proposed

HISTORY OF UNITED STATES PEACE CORPS INVOLVEMENT IN FRESHWATER AQUACULTURE

by

Gary L. Jensen

LIST OF COMMONLY USED ACRONYMS

AID - Agency for International Development
A - Associate Peace Corps Director
AU - Auburn University (Alabama)
BHN - Basic Human Needs
CARE - Cooperative for American Relief to Everywhere
CRS - Catholic Relief Service
CRSP - Collaborative Research and Support Program
CWS - Church World Services
FAO - Food and Agriculture Organization
HC - Host Country
IRT - Improved Rural Technology
OPTC - Office of Programming and Training Coordination
OSU - Oklahoma State University
OU - Oklahoma University
OXFAM - Oxford Committee for Famine Relief
PC - Peace Corps
PCV - Peace Corps Volunteer
PVO - Private and Volunteer Organization
UN - United Nations
UNDCF - United Nations Capital Development Fund
UNICEF - United Nations Children's Emergency Fund

INTRODUCTION

The Peace Corps (PC) was created in 1961 by the administration of President J. F. Kennedy to assist third world countries to meet the challenging and crucial basic needs of their people. Changes in government administrations have, on occasions, led to corresponding shifts in program policies and strategies, but major emphasis has been directed to projects and activities that enable the Peace Corps Volunteer (PCV), in conjunction with other resources, help people meet their own basic human needs (BHN). To effectively impact the living standards of rural and urban poor, grassroots-level projects aimed to directly reach target groups are of top priority.

In the beginning years, PCVs with non-specific skills, known as generalists, were recruited with minimal technical training and project programming. A period followed that was characterized by recruitment of specialists having more specific job-related skills complemented by additional technical training. The Office of Programming and Training Coordination (OPTC) was established in 1978 to coordinate volunteer placements and training, and country-level planning focused on joint development projects with host countries. The OPTC also provides technical backstopping support to on-going projects and functions to procure support funds for new projects. Since the formation of OPTC, volunteers of the generalist type again have been recruited and skill-trained volunteers (STV) are field posted on completion of training that includes the traditional language and cultural orientation with an additional intensive technical skill training component. A special Information and Collection Exchange (ICE) unit supplies technical manuals and references pertaining to appropriate technologies to volunteers on request.

PC has a long history of fish culture development since its inaugural project in Togo in 1966 and presently directs many programs in various stages of evolution. The major emphasis and contribution has been the dissemination of fish culture technology at the grassroots level. Fish culture volunteer groups receive practical, hands-on skill training in fish culture methods and practices in conjunction with agricultural extension methods, community analysis and involvement, health and nutrition. Technical training generally lasts 8-10 weeks and is conducted at a U.S. university with a recognized fisheries curriculum, in the host country, or both stateside and abroad. A key factor to project success is to field PCVs as trained fish culturists prepared to begin constructive work rather than as non-skilled generalists lacking credibility and having to learn by trial and error in-country with counterparts and/or farmers. The duration of a volunteer assignment is 2 years; however, some either inevitably terminate early or extend for an additional year. Compared to other PC sector programs, fish culture PCVs have an unusually high rate for third year extensions.

Fish culture projects concentrate for the most part on the development of small-scale rural fishponds which are used by farmers to generate both protein food and income. The fish culture program has expanded substantially and gained notable recognition since a fisheries specialist began work with OPTC in 1978. During fiscal year 1979, the number of fish culture PCVs increased from 150 to 270 and new programs were initiated in 10 countries. Volunteers have played effective, catalytic roles in developing

and advancing fish culture practices and programs, in part because of sound technical training directed by fisheries scientists and/or former PCVs, a rigorous selection screening during the training period, and technical backstopping support of field posted PCVs by OPTC.

PC has made significant progress through extension outreach projects in teaching small-holder farmers how to construct and manage fishponds and culture freshwater fish, often in areas with little or no previous history or tradition of fish culture. Volunteers have been responsible for writing manuals and extension pamphlets in host country languages, designing and supervising construction of fish farms and hatcheries, conducting applied research, establishing and organizing government infrastructures, transferring fish culture know-how to farmers and/or counterparts to foster self-dependency, and demonstrating the feasibility of fish culture through the use of appropriate technology and grassroot development. Action/Peace Corps has printed a fish culture manual and a program planning guide for volunteers in addition to making a training film on the controlled spawning of fish.

In many countries, primarily in the African region, PC has taken the lead role in developing fish culture projects, often with bilateral or multilateral collaboration with Private and Volunteer Organizations (PVO), the U.S. Agency for International Development (AID) or host country (HC) agencies. Professional aquaculturists are often employed as short-term consultants to assist in project design and planning and to provide technical support to projects. The strong performance record to date of many PC fish culture projects suggests continuation and further expansion in upcoming years.

The following summarizes the involvement of PC in freshwater aquaculture development from 1966 to projected activities for 1981 in a brief regional chronological account followed by a detailed account of each country listed alphabetically by regions. PC has been active in marine and lake fisheries, and mariculture projects. The following, however, is restricted to inland freshwater fish culture projects and activities. Some country information is incomplete or lacking because of an inadequate system for document and report storage and retrieval. The information herein was obtained from the files and archives of PC/Washington and from interviews with former PCVs. Special thanks are extended to Mr. Valdis Mezainis, former Fisheries Specialist and present Acting Director of OPTC, and to Mr. Roger Palm, present Fisheries Specialist of OPTC, both of whom provided PC documents and reports and experiential information.

COUNTRY INFORMATION

Peace Corps activity in freshwater aquaculture development is presented for the following countries.

Bolivia
Cameroon
Central African Republic
Chile
Colombia
Costa Rica
Dominican Republic
Ecuador
El Salvador
Gabon
Gambia
Ghana
Guatemala
Honduras
India
Ivory Coast
Jamaica
Kenya
Lesotho
Liberia
Malawi
Malaysia
Mali
Mauritania
Morocco
Nepal
Nicaragua
Niger
Nigeria
Oman
Philippines
Rwanda
Senegal
Sierra Leone
St. Lucia
Swaziland
Tanzania
Thailand
Togo
Upper Volta
Western Samoa
Zaire

African Region

Cameroon Involvement was initiated in 1968 with a feasibility study for fish culture development by a short-term consultant. The Government of Cameroon (GOC) requested formal assistance by PC in 1969 when 8 PCVs trained in intensive fish culture management were posted. The first group was assigned to assist more than 2,000 west Cameroonian farmers owning fishponds. The PCVs and counterparts made significant progress, which led to financial assistance from the U.S. Embassy Self-Help Fund and Oxford Committee for Famine Relief (OXFAM), a philanthropic organization of England.

Seven additional PCVs were posted in 1971 and four of the original eight extended for a third year term. The HC government, U.S. Self-Help Fund and OXFAM allocated money for the initial construction of a fish farm near Bamenda. The Self-Help Fund donated a D-4 bulldozer for construction of government fish stations and private fish farms. The extension work was intensified in 1973 with the arrival of 6 new PCVs. At this time, PC activity in several areas was phased out and left under the direction of trained counterparts.

In 1974, with major program advances in the Northwest, GOC requested 9 PCVs to expand activity to the Western, Eastern and Northwest Provinces and 5 PCVs to continue work in the Northwest and Southwest Provinces. Fish culture development expanded to the Eastern Province in 1975 with the arrival of 5 PCVs. Another volunteer group began work in 1976 and replaced those terminating in the East, North and West Provinces, and initiated activities in the Littoral and Central South Provinces.

Another group of 12 PCVs arrived in 1977 to support efforts in the Northwest and Southwest Provinces and reinforce on-going programs in other regions.

In 1978-80, new groups of 10 to 15 PCVs each were posted annually to broaden the program development and outreach.

The early volunteer groups received technical training stateside at Oklahoma University (OU); however, groups are presently being skill-trained in-country at government fish stations.

AID has provided some support funds while PC provides motorcycles and basic equipment items to

volunteers. To coordinate country activities and exchange information, mid-service conferences are organized and attended by representatives of the various participant and interest organizations.

The fish culture program has achieved notable success since 1969 and PC intends to continue posting volunteers until at least 1984. The overall project goal has been to improve the nutritional level and family income of the rural population by providing technical assistance to the fisheries program of GOC. The program has played the lead role in renovating and establishing government fish stations as supportive units for local farmers, generating public interest and acceptance in fish farming, and training counterparts and progressive farmers in the basic principles of intensive fish culture. PCVs have trained hundreds of farmers and counterparts, resulting in substantial production increases in both private and government facilities.

The Israeli carp was introduced into the country in 1970 for culture purposes. Most pond culture to date, however, has focused on the use of tilapia (Tilapia nilotica) as the principal pond fish, with T. macrochir, Clarias sp., nile perch (Lates niloticus) and black bass (Micropterus salmoides) assuming minor roles of importance. Program success is exemplified in the Northwest Province where efforts were initiated. The province has 4,000 to 5,000 ponds, 50 m^2 to 1 hectare in size, which are overseen by trained fisheries extensionists.

The long-term commitment and concentration of resources in limited areas, coupled with effective training of HC counterparts and farmers by PCVs, have contributed to achievement of a level of self-sufficiency in several provinces. In 1980, 30 PCVs were working with 140 HC extensionists in 7 provinces. A total of 3,550 farmers were operating 4,550 ponds with average productions ranging from 700-900 kg/ha/yr.

Central African Republic Work in fish culture development began in 1974 with the arrival of 5 PCVs. The goal of the Central African Republic (CAR) program is to assist in improving the standard of living in the country by making available a cheap source of protein in the form of pondfish. PCVs aim to introduce and/or ameliorate fish culture in designated areas, train counterparts and enable farmers to become totally self-sufficient. The first volunteer group was assigned to renovate and upgrade present fish stations, produce fingerlings for distribution to farmers, and assist farmers with pond construction and renovation, stocking, management and harvesting. The PC Director's Fund initially supplied $5,000 for motorcycles and fuel support.

In 1976, 10 new PCVs were posted and an additional 7 volunteers began work in 1977. AID provided $118,000 in 1977 to support extension work through direct contact with farmers, to renovate 10 abandoned fish stations and to construct 10 new station facilities.

There were 8 PCVs working with some 900 farmers owning about 1,300 ponds located in 6 regions of the country in 1977. Although the average pond size was less than 100 m^2, some 13,500 kg of fish were produced and consumed at the village level. Two PCVs conducted courses in fish culture at agricultural schools to train future agricultural extensionists in the basics of fish culture.

In 1978, 13 PCVs were working in the program and by September 1979 volunteers were working with 1,835 private ponds, a 66% increase since January 1976. The program has received counterpart workers from the United Nations Children's Emergency Fund (UNICEF) and financial assistance from the United Nations Capital Development Fund (UNCDF).

The program has contributed to an increase in production by farmers from an initial average of 800 kg/ha/yr to approximately 2,000 kg/ha/yr. The total number of ponds under management has increased substantially and each fish station services the needs of some 200 or more ponds. The estimated annual production of pond-raised fish increased from 7.8 MT in 1976 to 18.1 MT in 1978. The average annual income for a farm family from fish sales reached $48 in 1980, significant for a country with an average per capita income of $250.

In 1980, 6 new PCVs were added bringing the total to 15. Nineteen local fisheries agents paid by UNICEF funds and 10 counterparts were also active in the program. Presently, PCV groups receive technical training in-country; the first group was trained at OU and subsequent groups were trained both stateside at Auburn University (AU) and in-country.

AID approved funding of $50,000 for an Improved Rural Technology (IRT) proposal that will support the program in 1980-81. A Five-Year Proposal, which is an integrated effort of PC and the Food and Agriculture Organization (FAO) of the United Nations (UN) with a funding level of $282,000, has also recently been approved. The proposal will cover PC needs through the project closing date of December 1984.

CAR uses only T. nilotica as a pond fish in keeping with its goal of self-sufficiency among fish farmers. In some areas, rice-fish culture is being practiced. PC success in CAR has demonstrated that Central Africans can become successful subsistence fish farmers as a result of a carefully planned and supervised extension project.

Gabon Fish culture activity began in 1979 with 8 PCVs initiating work to renovate fish stations and introduce extension practices aimed to reach small-holder farmers and villagers. Major focus was to train HC personnel and local farmers to become self-sufficient in raising and propagating fish. Seven new PCVs will be skill-trained at OU and posted in 1981.

Gambia PC involvement began in 1978 with a feasibility study conducted by a short-term consultant followed by the arrival of 3 skill-trained PCVs in 1979 to initiate a pilot fish culture program. The pilot program was a joint effort of the government Fisheries Department, Young Farmers Clubs, PC and CRS. The Fisheries Department provided logistical support and counterparts, several Young Farmers Clubs constructed fishponds and CRS provided support funding. The first year of the project emphasized site selection and construction of ponds, while pond management and extension were priority activities for the second year. Three new PCVs will be skill-trained at OU and posted in 1981.

Ghana A group of 3 PCVs will be skill-trained at OU and posted in 1981 to work primarily as fish culture extension agents. The project focus will be to assist small-holder farmers in acquiring the basic know-how to successfully construct and manage fishponds for protein food and supplementary income. A proposal for IRT funding of $35,000 for a 2-year period has been submitted to AID.

Ivory Coast There has been little fish culture work done; however, 2 PCVs were active in 1979 and one volunteer collaborated with a tilapia cage culture project funded by FAO.

Kenya Several PCVs worked as trout culturists and fishpond specialists as early as 1974. They conducted some research, short-courses and on-the-job training of counterparts. A short-term consultant did a feasibility survey of the country prior to program expansion in 1978. The fish culture project grew to 8 PCVs by 1978 who worked to increase the production of fish both at government stations and private ponds. Six PCVs were posted in 1979 and ten will undergo technical training at OU prior to posting in 1981.

Lesotho One PCV was working in fish culture development in 1980.

Liberia PC conducted an inland fisheries feasibility study in 1973 and 2 skill-trained PCVs were posted in 1979 to work in fish culture development. Eight PCVs will be trained at OU and posted to expand fish culture activities in 1981.

Malawi One PCV will be skill-trained at OU and posted in 1981. Job duties will include extension and supervision of construction and management of a small demonstration fish culture station to be built with assistance from UNICEF. The major focus, however, will be development of a successful extension program through collaborative efforts with individual farmers. The PCV will also work with a HC counterpart.

A short-term consultant reviewed fish culture potential for PC in 1980.

Mali A short-term consultant assessed fish culture potential that led to the posting of one PCV in 1978. In 1980, 2 PCVs worked in fish culture development with assistance from AFRICARE. A joint PC/AFRICARE project proposal has been submitted to AID/Mali requesting a grant of $262,000 to AFRICARE to assist the government in developing a fish culture project over a 2-year period. Two PCVs will be skill-trained at OU and posted in 1981 to continue program activities of constructing fishponds, training HC personnel and integrating fish culture with rice cultivation.

Mauritania A fisheries consultant conducted a feasibility study for inland fish farming in 1980, but no PCVs have yet been posted.

Morocco A fisheries consultant conducted a fish culture feasibility survey in 1980 and plans presently include posting the first fish culture group of 6 PCVs in 1981, following technical training at OU. Work will focus on procurement of broodstock, construction of fingerling centers and identification of cooperating farmers to initiate extension activities. The project will receive support assistance from the HC government and CRS.

Niger One PCV began work in fish culture development in 1975. Over the years, 2 to 3 PCVs have been active in fish culture extension, with 5 working in 1980.

Nigeria The OPTC fisheries specialist and a consultant surveyed conditions to assess the feasibility for fish culture development in 1977.

Rwanda A feasibility study for fish culture development was conducted in 1977 by a PCV from Zaire and the fisheries specialist of OPTC. One PCV worked in fish culture extension in 1977-78.

AID provided $1,450,000 to support fish culture development for the period 1980-82. The project aims to increase the availability of nutritious food in the form of pond fish and to raise the income of farm families. PC plans to post some 12 PCVs over a 5-year period to develop self-dependency of Rwandan farmers to construct and manage productive on-farm fishponds. In-service training programs will also be conducted for government agricultural extension agents.

Senegal A fisheries consultant conducted a feasibility study for fish culture in the inland waters for PC in 1977. A vanguard team of 7 PCVs arrived in 1979, following technical training at OU, to demonstrate the feasibility of inland fish production, increase the protein level in people's diets and raise farmer incomes. The PCVs had HC counterparts and together supervised all aspects of the government fish stations and activities with cooperative groups, in addition to providing technical assistance to individual farmers.

AID is providing $161,000 over 2 years for purchase of motorcycles, a vehicle, equipment, and construction materials. Plans include construction of a fish culture station, training of Senegalese counterparts and extension outreach technical assistance to the primary beneficiaries, the rural farmers and their families. The project will introduce fish culture to the Senegal River Valley by establishing a small farmer extension program.

A group of 9 PCVs will be skill-trained at OU and arrive in 1981 to replace those of the first group.

Sierra Leone The fisheries specialist of OPTC conducted a feasibility study for increasing fish production in rural areas in 1977. The first group of 3 trained PCVs arrived in 1978 and were followed by a second group in 1979, which brought the total number of fish culture PCVs to 8 in 1980. The CRS and AID both have provided financial support to the project that is developing fish culture activity in three distinct regions.

Small-holder farmers are assisted with the construction and operation of fishponds to grow fish as a source of protein and as a cash crop.

AID provided $51,000 for project support in 1979 and additional financial support has been requested of AID as an IRT project. With increased AID participation, program expansion focusing on extension is forecasted.

Swaziland PC began fish culture work in 1978 with 2 PCVs who constructed, stocked and managed fishponds in cooperation with farmers, trained counterparts, and assisted in the management of two government fish stations. The project goal was to provide fish in the diet of Swazi people and teach them the techniques of fishpond management and fish preservation. In 1980, one PCV was involved in fish culture activities and plans include posting one new PCV in 1981, following technical training at OU.

Tanzania The fisheries specialist of OPTC conducted an inland fish culture survey in 1978. The government requested 12 PCVs in 1979 to assist farmers at the village level and school programs in constructing and managing fishponds. The project goal is to produce fresh pond fish in the rural sectors. Eight PCVs worked in fish culture activities in 1980 and eight skill-trained PCVs will arrive in 1981 as a replacement group. Each PCV is expected to work with 20 villages, schools and/or individuals in the construction, stocking, management and harvesting of fishponds.

Togo This country marked the initial involvement of PC in fish culture development worldwide in 1966. Fourteen PCVs were skill-trained at OU and posted in 1966 for a 2-year term. An additional PCV transferred from Nigeria in 1967. Work was centered at government fish hatcheries to increase the production of fish seed and demonstrate to farmers the feasibility of fish culture. Several PCVs worked to construct new hatchery facilities and extend technologies to individual farmers. Most of the PCVs had a host country counterpart.

Several PCVs extended for a third year to conduct important pond studies at the fish stations.

Upper Volta One PCV began work in 1976 to assist in the planning and construction of a new fish culture station in conjunction with FAO. Activities were later focused on pre-construction planning for an AID-supported fish station. The PCV had a Voltaic counterpart and wrote fish culture articles for appropriate technology journals on fish smoking and pond construction techniques in French. In 1980, 3 PCVs were trained and posted to work primarily as fish culture extension agents.

A fisheries consultant to OPTC and PC/Upper Volta have submitted an IRT proposal to AID for funding support of about $40,000 for a 2-year period.

Zaire PC initiated fish culture activity in 1973 with 3 PCVs who conducted a feasibility survey in the Kikwit area. The first team of 8 PCVs arrived in 1975 to work as extension agents to test the feasibiltiy of fish culture in the Bulungu Zone under the assumption that a successful trial effort would lead to an expanded program. An integrated approach to rural development was taken to incorporate fish culture as a complementary aspect of traditional small farmer agriculture practices.

In 1977, 5 additional PCVs joined the fish culture project to expand activities to new zones.

AID provided motorcycles through a Self-Help grant while OXFAM, American Baptist and Catholic Mission programs also provided vital support. Five of the eight PCVs who arrived in 1977 extended for a third year. The volunteers were successful in activating farmer interest and participation and raising the average production in 6 months from the traditional 2-3 kg/are to 20/kg/are in 1978 (1 are = $100m^2$). Each PCV, equipped with a motorcycle, worked with an average of 20 Zairois farmers in intensive fish culture. PC/Zaire had established one of the most successful limited-scale small farmer development programs in Africa: a pilot extension system to promote freshwater pond fish culture.

Work was also focused on the renovation of existing fish stations and establishment of new facilities. The goal was to construct small fish stations in new areas designed to meet the needs of the extension program. PC was also instrumental in introducing superior pond fish to replace less desirable indigenous fish.

The fisheries programmer of OPTC reviewed fish culture activities in 1977 and recommended establishment of an in-country training center and requested funding support from AID. The fish culture program has since expanded with a full-time fisheries Associate Peace Corps Director (APCD) to coordinate all regional programs and 50 PCVs active in grassroots-level fish culture extension. AID has provided long-term funding to assist small-holder farmers in producing fish, to develop and implement training capability suitable for both extension agent and farmer training, and to establish and operate regional fish seed production centers. The program has also evolved the capability to technically train PCVs in-country rather than in the United States.

Asia Region

India The first fish culture group of 15 PCVs received technical training at OU and began work in 1969. PCVs efforts were directed to extension activities and management of nursery ponds and breeding of carp at government fish stations. Accomplishments included renovations of defunct hatchery farms, successful pond culture of common carp, induced spawning of a major Indian carp, and rearing of young fish to stocking size for pond grow-out.

In 1971, a replacement group of 15 PCVs arrived to continue extension work and assist in operation of government fish farms. Work was aimed at improving facilities and management practices of government fish stations and expanding the extension program to individual farmers. The activities were continued by 7 PCVs arriving in 1973. PC fish culture involvement ended in 1975. One volunteer wrote a manual for fish culture that was widely utilized.

Malaysia The fisheries specialist of OPTC conducted an inland fish culture survey in 1978. There were 2 PCVs working part-time with fish culture activities in 1978. Three PCVs were active in fish culture extension activities directed to rural farmers in 1980.

Nepal Fish culture work began in 1969 with 2 PCVs transferring from agriculture duties to fish culture activities. The first formal fish culture group

of 6 PCVs was posted in 1971 with a following group of 8 PCVs arriving in 1972. Between 6 and 8 PCVs arrived each year in 1973-75, and some 12 PCVs were posted each year in 1976-79. The first group was skill-trained at OU and subsequent groups received technical training in-country conducted by former PCVs and HC personnel. Fish culture involvement terminated in 1980.

Throughout the years, PCVs were involved primarily in extension work, assisting farmers directly with problems related to site selection, pond construction and management, procurement of fish seed, record keeping, and, in some cases, teaching the farmers how to breed carp. Volunteers also assisted in fish spawning, fingerling rearing and distribution, and pond management at government facilities. Some PCVs worked with 4-H Clubs to develop communal fishpond projects and with farmers to prepare loan proposals for construction of fishponds. Generally, each PCV worked closely with 10-20 farmers, and thus was able to successfully teach the basic skills essential for raising fish. National fish culture surveys and many technical reports, including a manual on fish culture, were implemented by volunteers.

PCV activities have centered on BHN of nutrition and food and have resulted in expanded production of pond-raised fish through the educational training of fish farmers. PC provided early groups of PCVs with bicycles, scales and cast nets, while the 1978-80 group was given motorcycles, minnow seines and water quality test kits. Most volunteers had no permanently assigned HC counterpart. There is some discussion of PC resuming fish culture involvement in 1982 in collaboration with the HC government and an international fish culture development project.

Oman A consultant conducted a feasibility study for fish culture development in 1978 for OPTC. No PCVs have yet been posted.

Philippines PC has been involved in fisheries development in a large scale, with as many as 40-50 volunteers active in the same year. Program focus has been directed on aquaculture development in coastal waters.

The first freshwater fish culture group of 3 PCVs arrived in 1971 to work exclusively at government fish hatcheries to improve techniques for spawning and production of fish seed. Another group of 6 PCVs arrived in 1972 to continue the hatchery-related activities and expand the program to include fish culture extension. New groups, each consisting of 4-6 PCVs, arrived in consecutive years during 1973-76. Most efforts continued to be directed to the management of government fish stations with some extension outreach to individual farmers. Some volunteers extended activities to cage fish culture, eel culture and rice-fish culture. PCVs disseminated technical information to interested farmers and authored scientific articles in HC journals. Several PCVs were also involved in research and project planning.

Few volunteers were recruited to work specifically in freshwater aquaculture after 1978. One PCV, however, initiated interest in rice-fish culture in a mountain province which eventually resulted in a support grant from the Asia Foundation, AID and Cooperative for American Relief to Everywhere (CARE) to establish a pilot fish station in the region.

The goal of PC/Philippines in fisheries development is to assist in accelerating the production of fish to establish national sufficiency through extension services, marketing, and fishpond management. PC has initiated a Fisheries Development Program (FDP) in cooperation with the government to explore and develop the country's aquatic resources. Cooperative projects through FDP have been initiated with the Bureau of Fisheries and Aquatic Resources (BFAR), the University of Philippines, and provincial and municipal governments.

Thailand In 1977, 3 PCVs were active in fish culture development devoting efforts to establishing demonstration fishponds, induced spawning of local fish, teaching farmers improved management practices and training counterparts. Four PCVs were requested in 1979 to work as fish culture extension agents with responsibility for both technical implementation and extension service of inland fish culture projects addressing the needs of rural farmers.

In 1980, 6 PCVs were working in the program, while 4 new PCVs will arrive in 1981 following technical training at OU.

Caribbean Region

Dominican Republic The first group of 3 PCVs arrived in 1979 to work as extensionists in association with the government Agrarian Reform Institute and a pilot project initiated by Church World Services (CWS). The goal of the project is to develop inland fish production among 1,200 rural families to improve nutritional and economic standards. The PCVs received 9 weeks of technical training at OU prior to country arrival.

A number of PCVs were previously involved in fish production as a secondary activity. The OPTC Fisheries Specialist conducted an inland fish culture survey in early 1979 that led to the development of the project.

Projected plans include technical training at OU and posting of 4 new PCVs in 1981 to expand the extension effort.

Jamaica Four PCVs began fish culture work in 1976 in collaboration with the Ministry of Agriculture with assistance from AID. Three new PCVs arrived in 1979 and the program expanded in 1980 with the added participation of 7 PCVs. The 1979 group worked with management of hatchery and fish production facilities and with communities to establish fish culture projects preferably integrated with other agriculture and livestock projects within the same community.

A new group of volunteers arrived in 1980 and worked in hatchery production, pond construction, extension and marketing. Ten more PCVs will be skill-trained at OU and posted in 1981.

St. Lucia Two PCVs began work as aquaculture specialists in 1980 on completion of technical training at OU. PC is involved in a long-range project aimed at increasing the local production of protein foodstuffs

that will be available to inland areas in St. Lucia. The Ministry of Agriculture plans to establish freshwater fish culture as a means to decrease imports of fish and related products and to offer an alternative crop at the subsistence level.

The volunteer duties include location of suitable sites for pond culture, promotion of fish farming, management of government operated fishponds, investigation of indigenous fish for pond culture, and execution of extension work.

Plans include technical training and posting of 4 new PCVs in 1981 to continue support in the on-going program.

Latin American Region

Bolivia No formal fish culture project has been initiated, however, a PCV was active in promoting fish culture development in 1963-65 and authored an extension pamphlet pertaining to culture of fish in ponds.

Chile The government has requested the services of 2 PCVs to begin work in 1981 in an inland fisheries pond culture project. The volunteers will receive technical training at OU prior to country arrival.

Colombia PC has had no formal fish culture project; however, 2 PCVs did some work related to fish culture in 1976 and one authored a guide to the culture of trout in a reservoir.

Costa Rica PC involvement in fish culture began in 1969 and continued for several years with only one or two PCVs. The first volunteers were posted at a fish station in Turrialba that was a component of a FAO diversification project. They conducted pond yield trials, assisted in station management and extended technologies to local farmers.

PC renewed activity in 1980 when 4 PCVs were posted to work primarily in extension outreach to farmers. A feasibility survey conducted by a short-term consultant and technical training at OU preceded the country postings. The PCVs work in association with government fish stations and provide technical assistance to station managers in addition to private pond operators. The Catholic Relief Service (CRS) has provided about $3,000 for project support in the form of motorcycles and basic equipment and supplies.

Ecuador Involvement with inland fisheries development was initiated in 1975 with the arrival of 7 PCVs. Five worked in fish culture extension/demonstration activities and two began work with freshwater shrimp.

In 1977, two additional PCVs continued activities in the south working in collaboration with PREDESUR, which supplied motorcycles and basic equipment/supply items. They designed and supervised the construction of fish hatcheries and were active in extension; each also had a HC counterpart. Fish species cultured included Tilapia nilotica, Israeli carp, grass carp and native fishes.

Some PCVs initiated a pilot project that operated in 1976-78 in the Province of El Oro. Thirty-five ponds were constructed for demonstration purposes and reproduction of carp and tilapia. Based on the production results from these ponds, an extension program was launched to reach farmers in the region.

Eight technically trained PCVs entered the fish culture program in 1980 and 7 more will join activities in 1981, on completion of technical training at OU. Fish culture development will be intensified in the southern Provinces of Loja and Zamora-Chinchipe.

El Salvador The inland fisheries program began in 1970 with 3 PCVs working in fish culture. One PCV was responsible for the management of a government fish station and conducted applied research. Two PCVs worked in extension, providing technical assistance to farmers, conducting an inventory and survey of fishponds and writing an extension manual for fish culture. The program received funds from AID to puchase two vehicles and miscellaneous field equipment and supplies. Each PCV was assigned a counterpart to expedite progress and allow transfer of skills aimed to establish HC personnel independency. Both the PCVs and their counterparts received 8 weeks of technical training in fish culture at Oklahoma State University (OSU).

In 1972, replacement group of 3 PCVs arrived to work in extension, conduct marketing surveys for freshwater fish, and investigate the use of predator/prey culture systems, agricultural by-products for feed formulations and fish harvesting schemes. A third group of 6 PCVs was posted in 1974 after receiving skill training at AU to expand the extension program to schools, rural communities and commercial fish farms. Research was continued at the government fish station on feed formulations and predator/prey species densities. Several technical reports were published. PC provided a motorcycle to one volunteer and technical information and small equipment items to all. The last group of 5 PCVs entered the country in 1976 to continue work in extension and research. The program was phased out in 1978 because of HC counterpart capabilities to manage and implement the national fish culture program.

Guatemala One volunteer initiated work in 1976 as a project designer for the government. He also was an extensionist for a rural development project of World Vision International. The first group of 7 fish culture PCVs arrived in 1978. Technical skill training was provided in-country. Technical assistance was given to the government and farmers. The Government of Guatemala provided motorcycles to the extensionists with a fuel allotment, while PC fulfilled basic equipment needs. One PCV, stationed at a government fish culture center, had a counterpart and together developed an extension program for local farmers.

A replacement group came in 1980 and increased the number of PCVs to 12. About one-half were skill-trained in-country and the others at OU. Work focused on extension to assist small-holder farmers construct and manage fishponds. Plans include the establishment of small fish stations in rural areas to supply fish seed, and assistance from a PVO to provide counterparts and some financial support. A

project proposal has also been submitted to the AID country mission requesting support funding.

Honduras One PCV working in artisanal fisheries development began providing routine fish culture technical assistance to the government in 1975. Three PCVs with fisheries backgrounds and training at AU arrived in 1976. Work included teaching fish culture at a government agriculture school and extension assistance to farmers. The first PCV taught fish culture principles and practices to rural school teachers, initiated steps for a pilot fish culture project, participated in formation of a 5-year aquaculture development plan, began extension work with agricultural cooperatives, and trained new incoming PCVs. One PCV from El Salvador transferred to extension work and one new PCV served as an economist in the fish culture project in 1977. Two new PCVs entered the program in 1978 to work as extensionists. Two additional PCVs will be trained at OU and posted in 1981.

The project goal is to increase the availability of relatively low-cost fish protein to low income families in three selected country regions. The PCVs have renovated one hatchery facility, conducted surveys of existing ponds, constructed several ponds at agricultural schools and renovated private fishponds.

Nicaragua One PCV initiated fish culture work in 1977 for expanding production of freshwater fish to rural families. No formal fish culture project has developed to date.

Oceania Region

Western Samoa Two PCVs will be skill-trained at OU and posted in 1981 to initiate PC work in fish culture development.

PART 2

PRINCIPLES OF POND AQUACULTURE

BIOLOGICAL PRINCIPLES OF POND CULTURE: AN OVERVIEW

by

William Y.B. Chang

INTRODUCTION

The purpose of this and the following five papers is to report the state of knowledge on the principles of pond culture. Emphasis is on the ecological dynamics of factors related to maximizing fish* production. Ponds used in aquaculture differ in origins, structure, function, and geographic location and exhibit marked differences in fish production. However, this production is essentially governed by interactions among the physical, chemical, and biological conditions of the water and the species of fish or fishes present.

POND CLASSIFICATION

Recognizing the limitations inherent in any classification of pond systems from a production standpoint, the following classification is adopted here for purposes of convenience.

1. warmwater low intensity fish production ponds,
2. warmwater high intensity fish production ponds,
3. coolwater ponds (generally at high elevation or high latitudes), and
4. brackish water ponds (including mangrove swamps).

Although the principles of pond culture are similar for all of these four broad types, the quantity and quality of information available differ greatly among them. Among the types, there are physico-chemical and operational differences including origin (natural vs. manmade), stocking density, kind and amount of fertilization, fallowing periods, supplemental feeding, and the fish species used either in monoculture or in various levels of polyculture.

STATE OF KNOWLEDGE

Available knowledge is greatest for warmwater ponds that are intensively managed, least for coolwater ponds, and needed research differs accordingly. Solutions to narrow but highly technical problems, mainly dealing with transfers between trophic levels, are most needed for intensively farmed ponds (Figure 2) and brackish water culture systems (Figure 4). For low-intensity production (Figure 1) and cool water ponds (Figure 3), which are less well studied, broader research topics, such as feasibility, selection of species to be cultured, and relationships within trophic levels are the most needed and promising areas of research.

Ponds in the tropics differ considerably from those in temperate regions. As the majority of research in aquatic ecology and physiology has been done in temperate waters, it is important here to focus on some of these differences. For example, lowland ponds near the equator show only slight seasonal variations in temperature compared to those in the temperate zone. Most tropical ponds experience stronger seasonal variation (wet vs. dry season) than temperate water bodies. Equatorial high-altitude, coolwater ponds (predominantly Andean) may show large diel changes in temperature that remain relatively constant over the year. The foregoing examples are only illustrative; much more detail can be given to precisely delimit (perhaps by biogeographical region) the average and range of physico-chemical conditions present in each pond type in relation to bio-production. Among these conditions, examination of the role(s) in production of such previously obscure factors such as naturally occurring trace elements (e.g., cobalt, molybdenum etc.) and dissolved secondary compounds of aquatic and terrestrial plant manure (tannins, saponins, and alkaloids) along with metabolites of aquatic organisms themselves may prove valuable for managing aquaculture systems. Such a perspective will be of unusual importance in the application of information or transfer of technology from one geographical area to another. Comparison of pond ecosystems with marked production differences in the same geographical area is an efficient way of exploring important parameters which affect production in them -- here what is learned from the "good" may be used to alleviate problems in the "poor" and from the "poor" to avoid future problems in the "good."

*The term fish as used herein includes finfish and shellfish (principally shrimp and prawns).

POND DYNAMICS

Four conceptual models (Figures 1-4) graphically display interactions among compartments in the four types of pond culture systems. These models also show something of the intricate nature of pond productivity the relative importance of the factorial interaction of various components, and linkages of these components in a system. The relative productive importance of the interactions among components differs (as represented by the boldness of the lines connecting the compartments in the figures). These differences can be grouped under three major headings: physical; chemical; and biological. The selected research topics important to each compartment or trophic level are indicated in the lower part of the compartment. The emphasis, however, should be placed on the process(es) involved in the relationship and/or transfers between trophic levels.

Thus, the five major dynamic areas discussed in the following papers deal with: (1) bacteria and nutrient cycling; (2) benthos and sediments; (3) phytoplankton and macrophytes; (4) zooplankton; and (5) fish. A brief overview of these topics is presented below.

Bacteria and Nutrient Cycling

Successful management of an aquaculture system depends on a constant supply of basic nutrients necessary for optimal growth of the cultured species. This pervading fact is particularly important in extensive culture systems where food sources for the propagated species are maintained internally, as are most of the essential nutrients such as nitrates, phosphates, and carbon-containing compounds. The constant supply of nutrients depends heavily on rapid recycling, which is one of the most important factors in maximizing production in the pond culture. Phosphate and nitrate play a significant role in the production of aquatic organisms, especially micro- and macro-plants, and rely on the biochemical process of recycling for their conversion into a form available to the organisms involved. Discussion of nutrient cycling processes is provided in this study. As nutrient cycling cannot be accomplished without the assistance of bacterial activity (for example, cycling of nitrogen depends on the activity of both nitrifying and denitrifying bacteria), a discussion of nutrient cycling is provided in connection with bacteria. The discussion is also extended to cover the roles of bacteria as removers of substances toxic (NH_4^+, NO_2^-) to the cultured species and as a food source for plankton, which in turn become direct food items for the cultured species, or indirectly so for the small animal organisms on which they feed.

Benthos and Sediment

Inasmuch as the supply of nutrients is also dependent on the fertility of the indigenous soil and/or on soft sediment, which provides living environments for bottom organisms and which can variously affect the productivity of an aquaculture system, a discussion of these issues is presented in a subsequent section. As might be expected, it shows that pure (inorganic) sand provides the least productive environment, and fine silts and muck, the most productive. The annual productivity of some cultured species is directly proportional to the organic carbon content in soil. Under anaerobic or reduced conditions on the sediment surface, nutrients and some ions are released to the water, whereas the overlying water is kept at oxygen saturation in most aquaculture systems. The net flow of nutrients is from water to soil, with the soil acting as a sink for nutrients. Regeneration of these nutrients then comes primarily through biological interaction at the soil-water interface and through subsurface mixing such as bioturbation, in which the oligochaete worms and certain insect larvae act as conveyor belts to redeposit subsurface sediment at the soil-water interface.

Benthic algae and bacteria, which are directly controlled by the soil type, can form a watery (subaqueous) horizontal layer on the sediment surface. They often create chemical gradients by providing an increasingly rapid flux of nutrients from the soils, and also serve as food sources for species such as milk fish. A discussion of these topics is therefore provided in connection with the section on benthos and sediments.

Phytoplankton and Macrophytes

The growth of phytoplankton and aquatic macrophytes is known to be critical for augmenting fish production in pond culture, especially as most fish raised in warmwater ponds in less developed nations are dependent largely upon natural foods. The section on phytoplankton and macrophytes provides a synthesis of the relevant literature between these plants and fish yields. As managed fish ponds are often fertilized, and have nutrient concentrations which are generally elevated and primary productivity greater than the average natural water, the impacts of excessive fertilization are discussed. Included among these impacts arising from phytoplankton blooms are a lowered level of light penetration, a reduced compensation point which may depress productivity per unit area in the pond, reduced species diversity, and stimulation of unwanted species of algae such as certain blue-greens, which can limit light penetration, lower CO_2 concentration, and deplete nutrients in surface water. These conditions can lead to massive and disastrous die-offs from severe depletion of oxygen following decay of the dead algae. Preventing such blooms is of great concern to many intensive aquaculturists. Some success has been achieved by manipulation of nutrient levels where varying N/P ratios result in changes in the dominance between blue-green and other types of phytoplankton.

The occurrence of macrophytes is normally considered to be undesirable in most kinds of pond management because they compete with phytoplankton for nutrients and interfere with the fish harvest. However, there are occasions when aquatic macrophytes in fish ponds become beneficial as food sources for certain fishes or serve as expanded host substrates for attached and/or clambering invertebrates, which are food for some fish.

Zooplankton

In low and/or moderately managed systems, a good relationship has been found between secondary production and fish yield, but zooplankton populations have been measured infrequently in most aquaculture

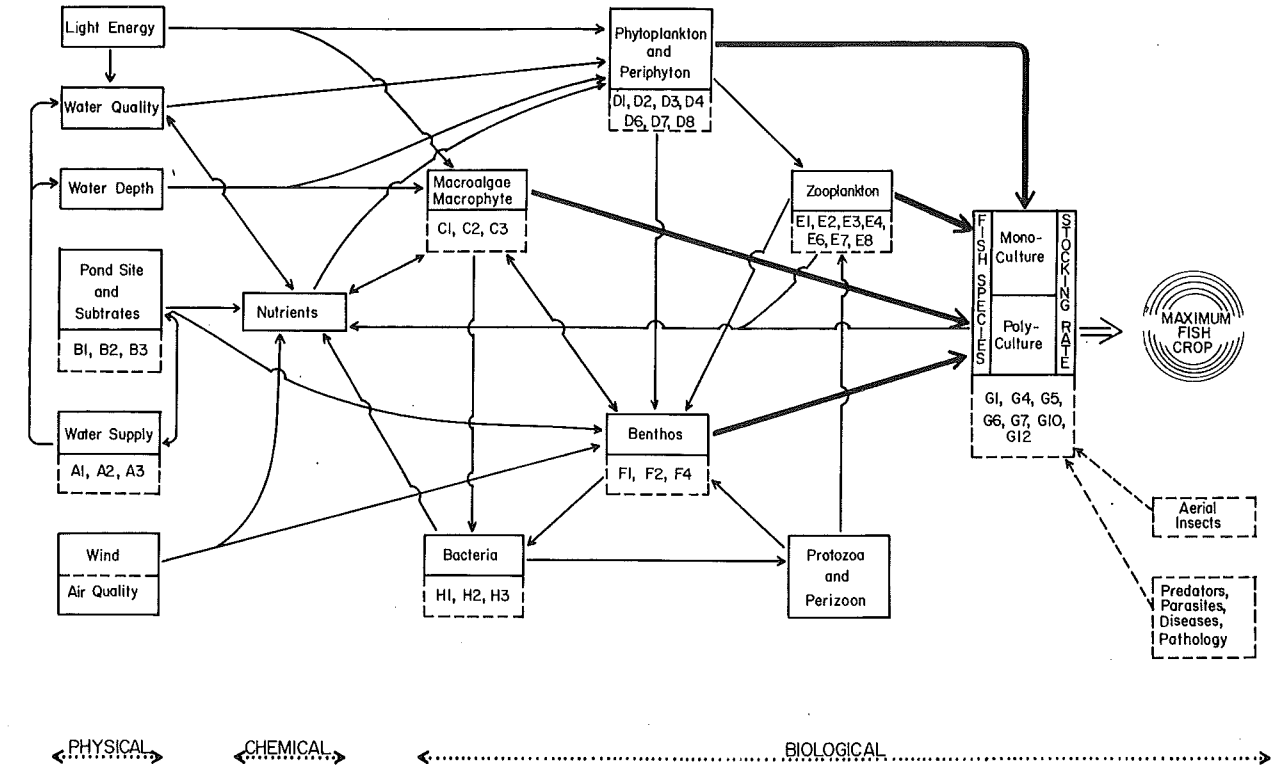

Figure 1. Low intensity tropical ponds.

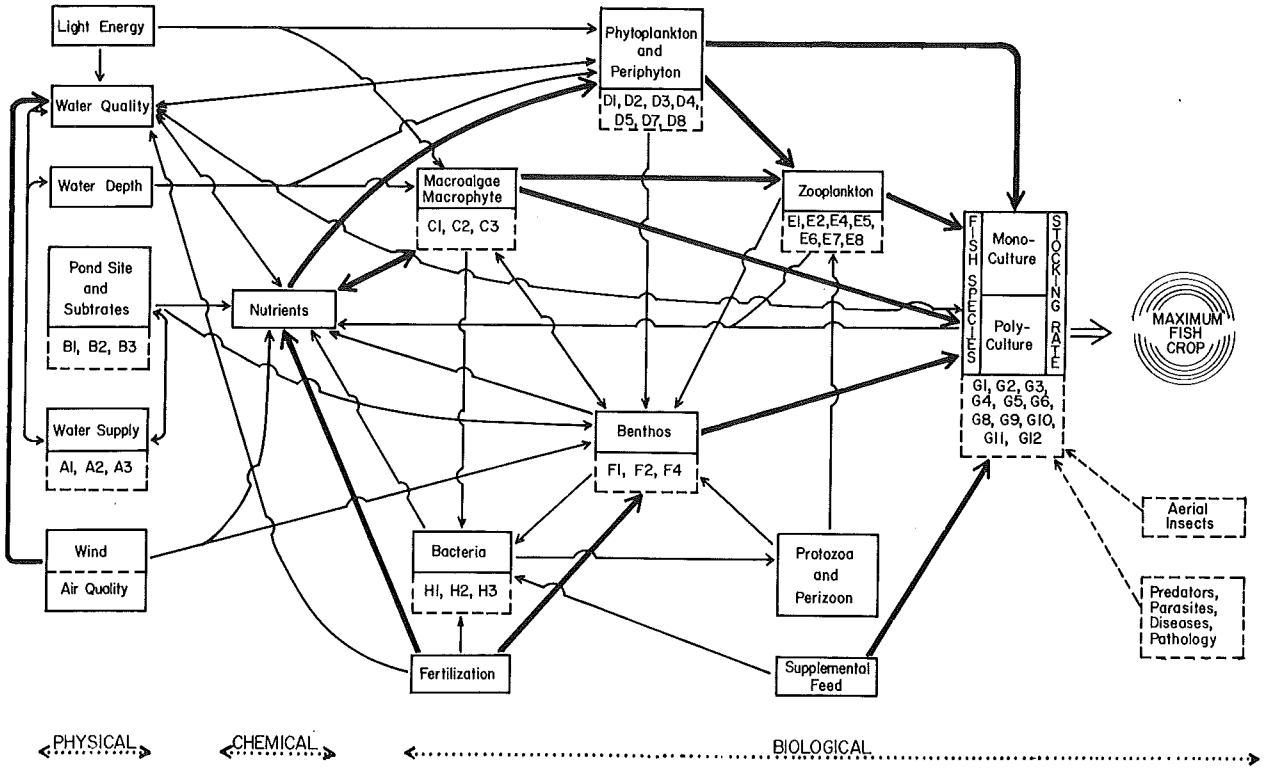

Figure 2. High intensity tropical ponds.

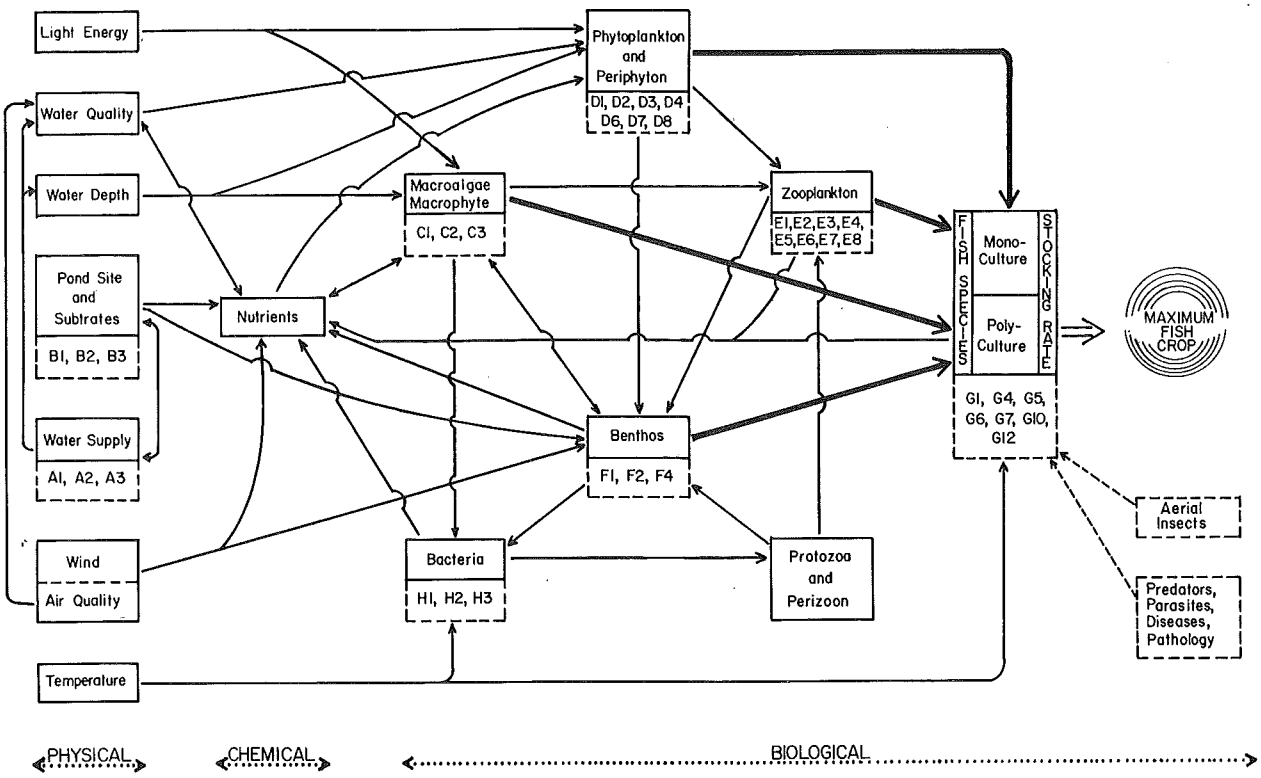

Figure 3. Cool water tropical ponds.

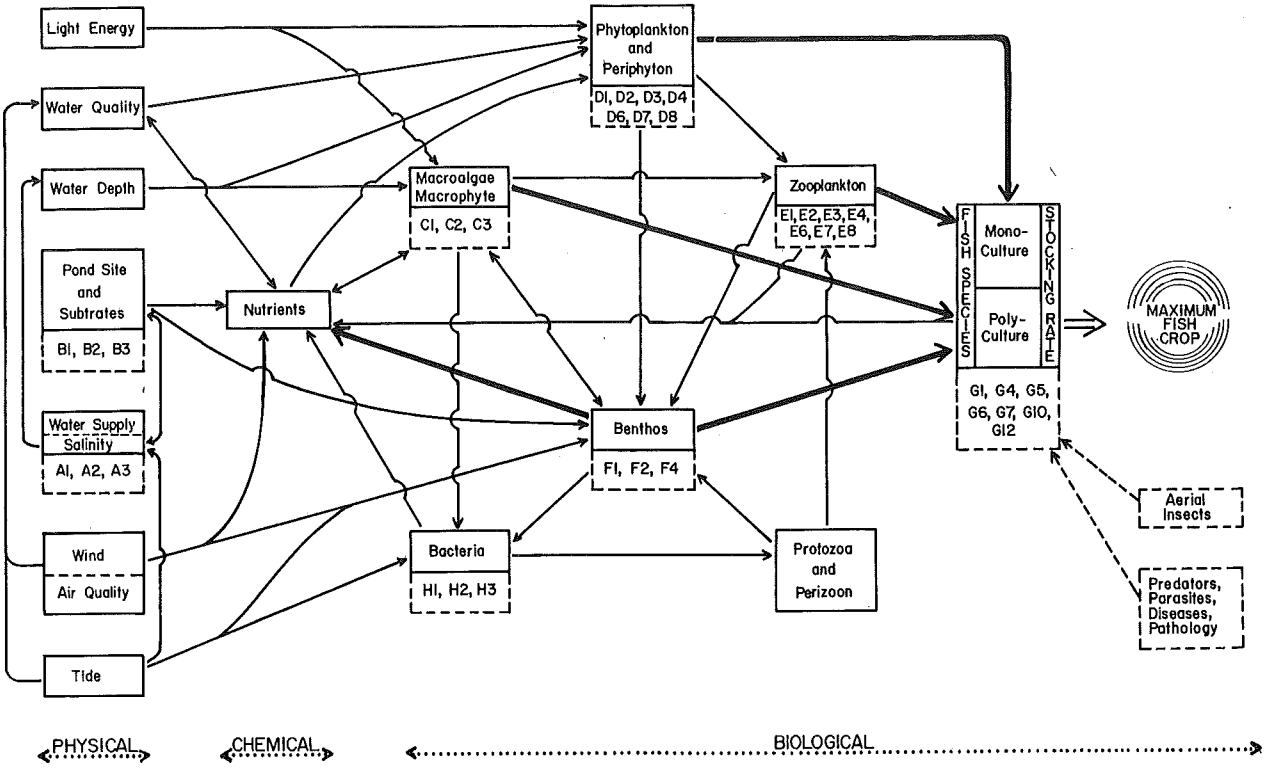

Figure 4. Brackish water ponds.

systems. Nonetheless their role in fish culture is important, and their abundance and composition are clearly affected by fish standing stocks and they can influence the fish yield. A strong correlation has been noted between food conversion rate (kg feed supplied: kg fish yield) and zooplankton standing stock at zooplankton densities of 0.1 to 1.1 mg dry weight/L, but this correlation appears to be weakest at the highest zooplankton densities. The supply of zooplankton in this instance is important in fish production, and is also important as a food for many species of fish fry. In many intensively managed systems zooplankton is grown to improve the survival of the early developmental stages of fish. For example, the rotifer Branchionus and the brine shrimp Artemia are commonly reared as food items for fish fry. In addition, it is to be noted that the maximum growth of fish fry depends not only on having the proper number and size of zooplankton present as food items, but also on having these zooplankton contain the appropriate nutrients. Other than the positive association between zooplankton and fish, some zooplankters can also act as predators on fish larvae. For example, cyclopoid predation on fish larvae occurs commonly and has been reported by a number of freshwater and marine researchers. Certain species of copepods are also fish parasites. They damage the fish either by disrupting tissue or through encouraging secondary infections. When this occurs, there can be extensive negative effects on fish production in a high density culture system.

Fish

The major goal of this investigation is to provide information on principles related to achieving optimal fish production, which is intimately affected by stocking density (and species mix in polyculture), mortality, and growth in individual weight. These parameters are then related through mechanisms of biotic interaction with physico-chemical environments. Growth relations with density are thought to be the most important areas for research on pond culture for fish production. The rationale for this focus is detailed in a subsequent section, where the ecological and physiological mechanisms governing managed and natural reproduction, growth, mortality, and recruitment to harvestability of fish are discussed extensively with respect to those species commonly cultured in tropical ponds. The effects on growth in individual weight of the cultured fish stock are organized into the following categories: (i) intra- and inter-specific competition; (ii) effects of antagonism and facilitation; (iii) abiotic limiting factors; (iv) effects through efficiency of food conversion and assimilation; (v) nutrition and diet; (vi) endocrinology and genetics; and (vii) pathology and growth (growth influences due to dietary deficiency-related diseases or bacterial, viral, and parasitic diseases). The integration of these factors is examined through a bioenergenetic model which illustrates the effects on fish production of various primary mechanisms and ecological principles. This model provides an in-depth overview of indirect components which interact with fish culture, offers explanations for high yield of polyspecific culture systems, and highlights impacts stemming from various aquaculture practices.

BIOLOGICAL PRINCIPLES OF POND CULTURE: BACTERIA AND NUTRIENT CYCLING

by

Russell Moll

An important aspect of successful aquaculture system management is a constant supply of basic nutrients necessary for optimal yield of the cultured fish (Edwards 1980). This fact is especially important in extensive culture systems where food sources for the culture species are typically maintained internally, as are most of the nutrients such as nitrogen, phosphorus, and carbon compounds. Adding manures to a pond or culturing tank as a method of ensuring a proper nutrient balance may also be used in intensive cultures. Irrespective of the method used, nutrient cycling is one of the most important factors in efficient aquaculturing.

Nutrient cycling involves a number of chemical and biological processes, but a major contributor is bacteria, which utilize substances in the water and sediments and make them available to other organisms in the fish pond. In fact, many of these substances can be harmful to other organisms in the system (Seymour 1980). It would be difficult to discuss bacterial activities in aquaculture without including nutrient cycling and, conversely, nutrient cycling could not be examined accurately without incorporating bacterial activity. Therefore, both subjects will be addressed in this section.

Many substances in the water and sediments of an aquaculture system are useful as nutrients. These substances include mineral salts, various carbon, nitrogenous, and phosphorus compounds (Fogg 1975). Of these, nitrogen and phosphorus compounds are usually found to have the greatest importance to primary production by aquatic organisms (Likens 1972). Excess phosphorus compounds do not have the same detrimental effects on an aquaculture system as do certain nitrogenous substances (e.g. NH^+, NO_2^-). This fact has supported studies on the removal of nitrogenous compounds or conversions to useful products. Nonetheless, levels of phosphorus compounds have a major effect on the amount of primary production in all aquatic systems (Rigler 1973). The ratio of P to C to N can cause changes in algal species composition as well as abundance (Schindler 1975) which in turn affect the entire food web.

Bacteria undergo a series of bio-chemical processes in aquatic environments which are beneficial in providing increased secondary production, if not essential to production (Kuznetsov 1970). Cycling of nitrogen through the biochemical activity of nitrifying and denitrifying bacteria accomplishes two significant ends: first, it removes substances toxic to the cultured species (e.g. NH^+, NO_2^-) and second, it produces useful nutrients which aid in increased production. The cycling of phosphorus, on the other hand, primarily involves mineralizing organic phosphorus compounds to inorganic forms available for algal uptake. Bacteria also decompose solid wastes produced by animals in fish ponds through the same mechanisms to recover nutrients as additions of organics (such as manures) to the culturing tank or pond.

Microorganisms are also useful as food sources for zooplankters which in turn become foodstuffs for fish (Schroeder 1978). Systems aimed toward more intensive production have successfully incorporated bacterial protein into feed pellets as a less expensive protein source than fish meal (Kaushik and Luquet 1980; Matty and Smith 1978; Atack et al. 1979).

A final aspect of bacterial presence in aquaculture systems is the pathogenic nature of certain bacterial species. Because this section primarily addresses bacterial nutrient cycling, only minor discussion will be made concerning pathogens in aquaculture. Pathogens seldom become a major setback in extensive culturing systems while their major damage is done in intensive culture systems.

NUTRIENT CYCLES

Nitrogen Cycle

The nitrogen cycle in aquaculture ponds is the most important biogeochemical cycle of these systems. Nitrogen is essential to sustaining high primary production; but nitrogen can also be toxic to many organisms in high concentrations. The correct balance of available nutrient and controlled wastes is necessary in any aquaculture system. Bacterial metabolism plays an essential role in controlling unwanted nitrogen as well as maintaining available inorganic nutrient levels. The exact form the nitrogen cycle takes in any pond or lake depends on the location of the majority of nitrogen associated metabolism (Kuznetsov 1970). Denitrification occurs in anaerobic sediments and waters, while aerobic waters support nitrification.

In aquaculture ponds, high levels of fish and shellfish metabolism result in the production of various nitrogenous waste products. The major nitrogen-containing substance released by these organisms is ammonia (NH_3), which reacts with water to become

the soluble ammonium ion NH_4^+. Either NH_3 or NH_4^+ is fairly toxic to aquatic organisms, as is nitrite ion (NO_2^-) and its aqueous counterpart, nitrous acid HNO_2. Through bacterial activity, ammonia and nitrate are metabolized to yield nitrate (NO_3^-), which is fairly safe for aquatic organisms and useful to phytoplankton as a nutrient source. The bio-chemical reactions which occur to produce nitrate are given below:

$$2\ NH_3 + 3.5O_2 \xrightarrow{\text{Nitrosomonas}} 2\ NO_2 + 3H_2O$$

$$NO_2 + 1/2\ O_2 \xrightarrow{\text{Nitrobacter}} NO_3$$

As can be seen from these two equations, the production of the end product, nitrate, is dependent on the presence of oxygen and the activity of Nitrobacter to metabolize nitrite ion. Colt and Tchobanoglous (1976) calculated that the doubling time for Nitrosomonas was 13 hours at 30°C and 14 hours for Nitrobacter. Therefore, in a closed or semi-closed recycling system, two problems develop in the normal nitrogen cycle. First, the bacterial flora cannot respond rapidly enough to prevent a buildup of toxic substances, especially nitrite, since ammonia must first be reduced to nitrite and then to nitrate. Second, oxygen can be rapidly depleted during nitrification and prevent further oxygenation of nitrogenous waste products.

Although Nitrosomonas and Nitrobacter are the most common genera of nitrifying bacteria, there are others. Some other nitrifiers include: Mycobacterium, Nocardia, Streptomyces, Micromonospora, Streptosporangium, Arthrobacter, Agrobacterium, Bacillus, Corynebacterium, and Pseudomonas (McCoy 1972). Several fungi have also been found to be nitrifiers.

Nitrification rates are greatly affected by pH values (Srna 1976). Higher pH values greatly increase the oxidation of ammonia to nitrite. For example, the rate constant for ammonium oxidation at pH 7.13 is about 1/3 of the rate at pH 7.78 in a multi-stage biological filter (Srna 1976), whereas oxidation of nitrite to nitrate occurs more efficiently and rapidly at lower pH values.

Ammonia may also be used directly by certain phytoplankton through the following equation:

$$\begin{matrix} NH_3 \\ NO_3 \end{matrix} + H_2O + PO_4 + CO_2 + \text{Light} \xrightarrow{\text{Photosynthesis}} \text{Organic} + O_2$$

When oxygen becomes depleted in the water column, or organic matter reaches the sediments, denitrification takes place instead of nitrification.

$$2NO_3 + CH_2O \xrightarrow{\text{Denitrification}} N_2,\ N_2O$$

The process of denitrification takes place only in the absence of oxygen and/or in the presence of large amounts of organic nitrogen. Denitrification is conducted by a variety of denitrifying bacteria, and primarily between pH 5.5 and 8.0. Thus, as a pond or lake becomes anaerobic because of high metabolism levels, nitrogen is tied up either as organic nitrogen in the sediments, or is converted to free nitrogen (N_2). Eventually, these pools of nitrogen will be oxidized back to nitrate. But, the short-term management of the proper balance of different nitrogen forms is essential to maintaining an aquaculture system.

Phosphorus Cycle

In many natural freshwater ecosystems, available soluble phosphorus is the essential nutrient limiting primary production. But, once supplies of nutrients are elevated by anthropogenic or other inputs, phosphorus tends to lose its position as the limiting nutrient; in these cases other factors such as water clarity or dissolved oxygen levels become essential for continued algal growth (Lean 1973). Nonetheless, the cycling of phosphorus remains a key aspect in the maintenance of primary and secondary production in all aquatic environments. Proper elemental ratios of C to N to P must be sustained for protein synthesis. For these reasons, the phosphorus cycle is just as important to aquaculture pond dynamics as the nitrogen cycle, although the two are fundamentally different (Wetzel 1975).

Phosphorus in aquatic ecosystems occurs as phosphate in organic and inorganic compounds. Free orthophosphate is the only form of phosphorus believed to be taken up directly by phytoplankton (Rigler 1973) and thus represents a major link between organic and inorganic phosphorus cycling in lakes. In natural waters, orthophosphate occurs in ionic equilibrium, i.e.

$$\text{as } H_3PO_4 \xrightarrow{pK = 2.2} H_2PO_4^- \xrightarrow{pK = 7.2} HPO_4^{2-} \xrightarrow{pK = 12.3} PO_4^{3-}$$

with $H_2PO_4^-$ and HPO_4^{2-} being the predominant species over pH range of 5 to 9 (Stumm and Morgan 1970).

The cycling of phosphorus in small lakes was studied by Hutchinson and Bowen (1950) and re-evaluated by Kuznetsov (1970). The results show that most of the inorganic phosphorus is quickly utilized by phytoplankton and littoral aquatic macrophytes. When these plants die, the phosphorus is carried as organic matter (usually as a ferric phosphate complex) to the sediments. If the sediments become anaerobic along with the overlying water, phosphorus is released back into the water column. This release of phosphorus from the sediments is caused indirectly by bacterial metabolism. Anaerobic muds are normally rich in reduced sulfur compounds because of the activity of sulfur bacteria (Kuznetsov 1970). The reduced, sulfur rich muds quickly reduce ferric phosphate to soluble ferrous phosphate which readily migrates from the sediments back into the water.

Thus, in small ponds and lakes with anaerobic bottom waters, phosphorus would primarily cycle through the sediments. Most small aquaculture ponds would be expected to have this type of phosphorus cycle. But, in larger or well oxygenated ponds, phosphorus cycling is primarily carried out by a large variety of bacteria in the water column (Rigler 1973). The uptake and release of phosphorus by pelagic bacteria in either organic or inorganic form has been difficult to quantify. Bacterial activity is influenced by temperature, availability of substrate, oxygen concentration, pH, and chemical composition of the substrate (DePinto and Verhoff 1977; Foree and Barrow 1970; Kuznetsov 1970). Jones (1972) observed a relationship between senescent algae and bacterial biomass; a rapid increase in the amount of decaying algal cells in the water column, such as when a phytoplankton bloom declines, is usually followed by an increase in bacterial biomass.

Despite large variability in decomposition rates, some preliminary estimates of inorganic release by bacterial metabolism have been made. Field estimates of P turnover have been particularly inaccurate in that liberated P is rapidly re-used and rarely measured as available soluble P. Fuhs (1973) and Charlton (1975) estimated that water column P was recycled from 10 to 34 times during one growing season. Fallon and Brock (1979, 1980) have estimated that 60-70% of the organic matter from decaying phytoplankton was decomposed in the water column, primarily in the epilimnion.

More exact rates of P release by bacteria are available from laboratory studies. Golterman (1973) found that 70-80% of the organic P released by algal autolysis was converted to inorganic forms within a few days. DePinto and Verhoff (1977) conducted a study of the regeneration of P and N in axenic algal cultures and bacteria-algae cultures. They found that the P released as inorganic soluble reactive phosphorus was very slow when axenic cultures were placed in the dark. On the other hand, the bacteria-algae mixtures liberated up to 75% of the total P pool after several weeks. The rate of regeneration of the soluble P was a function of the initial P composition of the algae; P-limited algae produced regeneration rates of 0.06-0.08 µg P/mg algae (dry weight)/day, while algae growing in P-rich media produced regeneration rates of 0.16-0.39 µg P/mg algae (dry weight)/day. DePinto and Verhoff (1977) stated that excess cellular P is stored in algae in an inorganic state. This would explain the much higher P regeneration rates from decaying algae growing in a P-rich environment. Therefore, bacteria mineralizing phosphorus-rich algal cells would likely be adapted to high levels of organic P while bacteria associated with P-limited algae would have slower regeneration rates and use more inorganic compounds for their P source.

BIOLOGICAL FILTRATION

The knowledge gained from the various nitrification and denitrification studies has been put to use in the development of specialized and efficient biological filtration units. A biological filter has a great advantage in the conversion of toxic nitrogenous substances to nutrients over natural microbial activity. The major advantage is that of concentration of functional species. Biological filtration units have immense surface areas of suitable substrates for growth and maintenance of nitrifying and denitrifying bacteria. Nitrifying bacteria require oxygen to carry out nitrification of ammonia and nitrite and biological filters offer the ability to fully aerate all surfaces where bacterial activity is maintained. Denitrifying bacteria require anoxic conditions to convert nitrate to nitrogen gas or N_2O. This can easily be accomplished by incorporating a second filter column to the system which is sealed from atmospheric conditions, thus maintaining an anaerobic environment. It should be noted here that all culturing systems do not need the added nitrification and denitrification capabilities of biological filters. Biological filters are basically used in intensive aquaculture systems where recirculating water is necessary due to short water supply.

NUTRIENT SOURCES

Many products, both natural and synthetic, can serve as nutrient sources or fertilizers for aquaculture systems. The most practical substances are products of natural sources which are readily available, inexpensive, and in most cases enhance ecological and aesthetic goals most effectively. These substances include animal wastes and other manures, composts, excreta from culture organisms, perished culture organisms, and some less likely sources such as petrochemicals and brewers' effluents.

In aquaculture, the greatest amount of research has been done regarding the use of various manures as the primary fertilizer for fish ponds (especially for cultures of Tilapia, common carp, silver carp, white amur (grass carp), and bighead carp). The manures which have been analyzed most for their efficiencies of producing useful foods for the fish are liquid cow manure, poultry manure, mustard oil cake, liquid swine manure, and human wastes.

The research and/or studies involving the response of aquaculture ponds to different nutrient sources have been primarily mechanistic in approach. The results have tended to show what type or amount of additives yield the best harvest from the ponds. In essence, the complexity of the various nutrient and degradation cycles are reduced to a simple "black box" approach. Various studies (Ghosh 1975; Behrends et al. 1980; Asare 1980; Wahby 1974) have identified efficient and successful results with different manures as nutrient additives. But, these studies do not recognize the interrelationships among the types of nutrient (which compounds), the necessary degradative process to change the form of the additive, and the size and activity of the bacterial flora required to conduct the nutrient degradation. Currently, the results from basic limnological studies of microbial nutrient cycling must be extrapolated to aquaculture ponds. Research should be initiated to determine if this extrapolation is valid, or if a different set of microbiological principles hold in aquaculture systems.

BACTERIA AS FOOD

The role of bacteria is not strictly limited to the recycling of organic nutrients; in aquaculture systems bacteria have also been used as a direct food source in the culture of plankton as well as useful protein sources for culture species (Atack et al. 1979). There are many aquatic organisms which devour

bacteria quite actively -- especially protozoans and zooplankton of the class Rotifera. Large populations of plankton can result from this process, which in turn serve as viable food source for secondary production.

Some fish ingest and digest bacteria when bacteria are associated with detritus eaten by detritivores (e.g. Tilapia) or through filter feeding by use of gill rakers. The bacteria which are ingested by filter feeders (e.g. silver carp) are generally attached to some larger organism or piece of detritus which is caught by the gill rakers or actively devoured. Schroeder (1978) showed that a two- to three-fold increase in fish yield occurred in ponds receiving chemical fertilization and manure treatments over ponds receiving only chemical fertilization, even though primary productivity remained the same. Abundance of large "food organisms" in the water also could not account for the difference in production. Therefore, it was determined that the fish were utilizing the bacteria and protozoans attached to detritus and particles of straw from the manures as a source of high quality protein. Autotrophic production is limited by the amount of light reaching the cells which decreases as phytoplankton numbers increase to a saturation point. Heterotrophs are not limited by light transmittance and therefore can continue to produce as long as nutrients are present for their growth and suitable aeration is maintained.

A more recent use of bacteria as a food source is that of bacterial protein in pelleted feeds. Fish meal is typically the major source of protein in pelleted feeds but is becoming financially unfeasible as the costs of this protein source increase. Bacterial proteins are relatively inexpensive and have been shown to be of high quality, being utilized well by the fish species tested (Kaushik and Luquet 1980; Atack et al. 1979). Another study showed little financial incentive for using bacterial feeds, but did maintain the feasibility of bacterial protein utilization in pelleted fish feeds (Matty and Smith 1978).

PATHOGENS

As in any system where living organisms congregate in large numbers, aquaculture systems are afflicted by numerous pathogenic organisms and diseases. Since the advent of more intensive culturing, pathogens have become an increasing problem in the process of raising fish and shellfish. It has also been found that disease problems are more acute in cold water aquaculture than in warm water cultures (Sarig 1976). Even in extensive culturing ponds the problems of disease can be very detrimental to good fish yields. Although the subject of pathogens is an important one, its significance to bacterial nutrient cycling is not very great. Therefore, only a brief discussion will be made of this highly diverse and complex subject.

The major preventative factor against disease in aquaculture remains proper management and husbandry practices; for example, maintenance of nutrient loads without large excesses, balanced nutrition for cultured species, maintenance of proper pH, and consistent monitoring and adjustment for changes in water temperature, ammonia concentration, and dissolved oxygen (Fisher et al. 1978; Sarig 1976).

There are many pathogenic bacteria, but the most commonly encountered groups are listed here: 1) Aeromonas and Pseudomonas, 2) Corynebacteria, 3) Enterobacteria, 4) Hemophilus, 5) Mycobacteria and Nocardia, 6) Myxobacteria, 7) Streptomyces, and 8) Vibrio (Sarig 1976).

There are many treatments for diseases in fish and shellfish once the pathogen has become a problem. These include various antibiotics which are usually added to feeds, vaccines (usually injected), and several chemotherapeutics (added to the culturing water). Other techniques which aid in prevention of pathogenic bacterial infections include ultraviolet light disinfection (Brown and Russo 1979), ozonation, and use of diatomaceous earth filters to reduce bacterial inflow to the culturing tanks or pools (Illingworth et al. 1979).

The use of chemotherapeutics presents a great risk of destroying the native bacterial population. Use of these general antibiotics tends to indiscriminately destroy both pathogenic and native bacterial flora and their associated processes. Thus, although a pathogen may be effectively controlled, the natural degradative processes will be arrested. Without these degradative processes, nitrogenous wastes will build up in the aquaculture system and nutrient supplies will become tied up in organic matter. In essence, a broad application of antibiotic may lead to a cure that is detrimental to the functioning of the entire pond system.

If human wastes are used as fertilizers in culturing ponds it should be realized that fish may be vectors of human infectious diseases. This is not a serious problem as fish are no more suspect than cattle, sheep, and other organisms which are cultured by man, but one should not assume that fish cannot be carriers of human diseases. Further research is needed to determine the extent (if any) of human pathogen-carrying capacities of fish and other cultured organisms in aquaculture (Janssen 1970).

FUTURE RESEARCH

Aquaculture is a practice which strives to maximize fish and shellfish yields with minimum energy inputs. Despite the evolution of the most efficient practices, much research has yet to be conducted before a useful understanding of aquaculture pond principles is developed. The role of bacteria in aquaculture has been only minimally examined and further research can be conducted in many areas.

Biological filtration has become widely accepted as an inexpensive and effective means of converting toxic metabolic wastes to useful compounds in culturing systems. Srna (1976) showed that studies on the kinetics of nitrification can aid in developing more efficient and compact biological filters, yet further research could be conducted to increase efficiencies in biological filtration units incorporating different substrates in various combinations.

Bacteria have been used successfully as inexpensive and nutritious substitutes for fish meal in pelleted fish feeds (Kaushik and Luquet 1980; Atack et al. 1979; Matty and Smith 1978). Research could be conducted to determine the most efficient combinations of bacterial and other single-celled proteins to use and which species of bacteria provide the most nutritious sources of protein.

As Schroeder (1978) observed, a large percentage of aquaculture production could not directly be accounted for in ponds receiving chemical and supplemental manure treatments, indicating that some source of nutrition was present that has as yet not been detected. It was determined that bacteria and protozoa provided the additional food to the cultured species. Further studies need to be conducted to verify this determination and to investigate how these organisms can be utilized more effectively.

Attempts have been made to isolate various bacterial groups to be used as reference strains for early warning detection of pathogens (Egidius and Andersen 1977; Gilmour et al. 1976). Investigation in this area could be expanded to encompass other pathogenic strains to develop a more complete and accurate early warning system to protect the vast investments involved in aquacultural endeavors.

Further studies into the use of bacterial activity indicators could prove beneficial, especially in ponds fertilized by manures as was shown by the use of cotton strips to measure cellulase activity in manured ponds (Schroeder 1978). This measurement would aid the user in determining maximum amounts of manure which could be added to maximize fish production.

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BIOLOGICAL PRINCIPLES OF POND CULTURE: SEDIMENT AND BENTHOS

by

David White

For most types of aquaculture systems, the relationships of sediments or "soils" and the benthic organisms occupying the soils are poorly understood. Further, the processes which occur at this level of freshwater and estuarian ecosystems have been examined in depth only within the past 20 years. Thus, benthic ecological theory is lacking in many potentially important soil-water processes. Much of the information in this review comes either from the general limnological literature or the aquaculture literature involving benthic feeding fishes. In practice, the relationship of soils and benthos to aquaculture should be applicable to and have a direct bearing on not only the culture of benthic feeders but also on other types of aquaculture in both cool and warm water, and in low and high intensity farming. In much of the aquaculture literature, soils and benthos are mentioned only in passing beyond pond site selection and manipulation. By example, Bardach et al. (1972) list fewer than a dozen citations directly related to the role of soils or benthos. This is somewhat surprising as the potential importance of soils in pond fertility has been known for some time (Pershall and Mortimer 1939; Mortimer 1949).

The origins and compositions of bottom soils are determined in part by the geological formations and soils of the basin, in part by autochthonous processes in the water column and the water-soil interface, and in part by allochthonous materials entering the system via runoff and anthropogenic sources. The benthic or bottom dwelling plant and animal community structure is directly related to the composition of the soils and is modified by the physiochemical conditions in the overlying water (Ruttner 1952; Hynes 1970).

Considered in this portion of the review is the role of soils as it relates to the benthic community which thereby influences aquaculture practices. It is assumed here that the pond site is active. Selection of the site and site preparation will directly affect sediments through potential loading as a function of the basin hydrology and site morphology (Bardach et al. 1972; Tapiador and Henderson 1977). The drainage patterns will influence a site through runoff of silts, human and animal wastes, agricultural fertilization, and toxins such as pesticides, herbicides, heavy metals, and toxic organics. Site dynamics must also provide for reasonable water circulation to prevent local areas of stagnation (Delmendo and Gedney 1976).

SEDIMENTS AND NUTRIENTS

The productivity of an aquaculture system is directly dependent on the fertility of the sedimentary soils with the type and texture being the basic governing factors (Djajadiredja and Poernomo 1972). Pure sands provide the least productive environments, fine silts and muck the most productive (Schuster 1949; also see reviews in Golterman 1977). The annual yields of some cultured species are directly proportional to the organic carbon content (Liang and Huang 1972).

Under anaerobic or reduced conditions in the soil and overlying water (if the pond stratifies), nutrients and some ions are released to the water. This process is independent of biologically mediated exchange. The magnitude and direction of the exchange process is proportional to the amounts of nutrients available. In most systems where soils contain silts and organic muck, the net flow of nutrients and ions will be from the soil to water. In most aquaculture systems, the overlying water is kept at or near oxygen saturation (Bardach et al. 1972) and the net flow of nutrients will be from water to soil, thus the soils act as a sink (Mortimer 1941, 1942, 1971; Fillos 1977). Regeneration of the nutrients in these systems primarily comes through biological interactions at the soil-water interface and subsurface mixing. Aquaculture practices can account for nutrient build-up in soils through various manipulations such as draining or flushing of pond sites and subsequent reworking the soils. Fig. 1 shows the typical annual pond manipulations in culture of milkfish (Chanos chanos, a brackish water benthic algal feeder) through data compiled from Bardach et al. (1972); Delmendo and Gedney (1976); Pillay (1972); Smith et al. (1978); Spotte (1979); and Tapiador and Henderson (1977). Following harvest, ponds are drained. While still moist, the soil is tilled to a specific colloidal texture based on the Atterberg scale (Liang and Huang 1972) and tested for levels of organic matter. If needed, lime is added to adjust the pH. Both organic and inorganic fertilizers are added as required, and then allowed to settle for 2 to 3 weeks. The site is then flooded minimally (1-10 cm) to induce the development of benthic algal culture. In this type of system, it is important that light penetrate to the soil surface for maximum algae growth over the next 1 to 6 weeks. The benthic or epipelic algae grown in this manner (along with the associated detrital aggregate) is the primary food source for the milkfish. Once a sufficient culture has developed, the pond is

flooded (35-100 cm) and restocked with fish of various sizes.

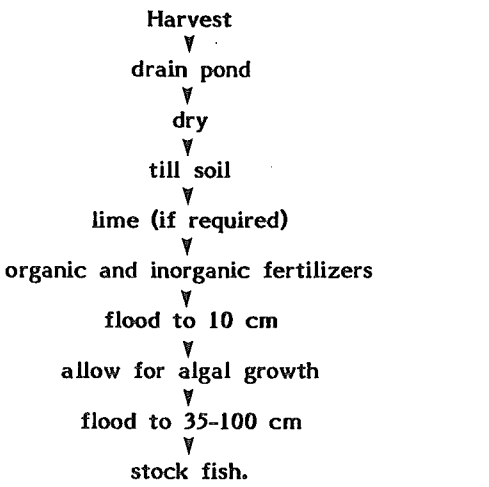

Figure 1

Pond manipulation for growth of benthic algae in milkfish (Chanos chanos) culture.

Species of cultured fish which directly feed on soils or the detrital components in the system (various carps, Tilapia) also rely on the quality and level of nutrients in the soil. For the Tilapia Sarotherodon mossambicus, Bowen (1980) has shown that it is not the amount of detrital aggregate available but the levels of nonprotein amino acids and their composition in the detritus that will determine growth rates. The detrital aggregate process may have a direct relationship to the level of nutrients in the soil coupled with more complex organic compounds in the water column. However, it is not truly known at this time what factors produce the detrital aggregate or how the nonprotein detrital amino acids are related to fertilization and maintenance of aquaculture systems (Bowen 1979, 1980).

SEDIMENT AND ALGAL-BACTERIAL RELATIONSHIP

The soil type directly controls the fertility of the aquaculture system, particularly algal and bacterial production in what has been termed the subaqueous horizontal layer (Rosell and Arguelles 1936). A list of some of the more important algal taxa is given in Table 1. Epipelic algae, both diatoms and filamentous, create chemical gradients by their uptake providing a more rapid flux of nutrients from the soils (Lee 1970). This, in turn, stimulates planktonic algal growth and nutrient uptake in the water column (Golterman et al. 1969). Release of nutrients from sediments under aerobic conditions is dependent on the types and densities of algae, and it is thought that the interaction with bacteria may control the form of nutrients released (Porcella et al. 1970). The exact mechanisms involved are not well known. Porcella et al. (1970) further found that mats of filamentous algae (e.g., Oscillatoria), which are a primary food source for species such as milkfish, may promote anaerobic conditions through metabolic activities in still water. The mats themselves disrupt soil-water mixing which further results in the release of organics and nutrients from the soils. From what is known, epipelic production and community structure may be directly proportional to nutrient contents of the soil, particularly nitrogen levels (see Patrick 1977 for effects of specific ions and nutrients on algal growth).

Effective aquaculture practices often require the selective growth, protection, and replenishment of desirable epipelic algal species (Blanco 1972). Improper nutrient balance or overfertilization of the soil may accelerate nutrient release sufficient for both epipelic and planktonic algal blooms. Such blooms often are responsible for fish mortality and/or fish flesh taste deterioration. In brackish water pond culture, nutrients from soil fertilization provide the basis for growth of "lab-lab," a complex of epipelic diatoms, green and blue-green algae, and the associated benthic fauna of protozoans, copepods, worms, insect larvae, etc., which together serve as a staple for benthic feeding fish (Gopalakrishnan 1972).

Bacteria, while usually not serving directly as a food source for cultured fish, function in releasing or rereleasing nutrients from soils, particularly in the detrital aggregate component, by assimilating various organic compounds (Neilson 1962). Decomposition and assimilation mechanisms are poorly understood but are known to be greatly enhanced by larger benthic invertebrates and fish which physically stir the soils (Hargrave 1970; Provini and Marchetti 1976). The mixing process primarily allows for greater contact with overlying water. This creates more effective bacterial activity as higher nutrient gradients are produced.

Table 1

EXAMPLES OF BENTHIC ALGAE AND MACROINVERTEBRATES ASSOCIATED WITH SEDIMENTS IN AQUACULTURE, PRIMARILY FRESHWATER

Diatoms	Benthic Invertebrates
Caloneis spp.	Tubificidae (Oligochaeta)
Diploneis spp.	Tubifex spp.
Fragilaria spp.	Limnodrilus spp.
Gyrosigma spp.	Gastropoda
Navicula spp.	Cerithidae spp.
Pinnullaria spp.	Physidae spp.
Nitzschia spp.	Lymnaeidae spp.
Surirella spp.	Insecta
	Chironomidae
Filamentous algae	tribe Chronominae
Oscillatoria spp.	in particular.
Cladophora spp.	

The presence of toxic substances and antibiotics which kill bacteria or limit their growth may alter rates and modes of decomposition and assimilation (Fillos 1977; Hayes and Phillips 1958) causing distinct changes in overall productivity of a pond system. The

magnitude and direction of the changes, however, are not predictable.

SEDIMENT AND MACROBENTHOS RELATIONSHIPS

The larger benthic invertebrates (Table 1) enhance exchange between soils and water not only by metabolic processes but by directly feeding on soils and detritus which increases porosity, mixes soils, and alters particle size (Fisher et al. 1980). Such mechanical changes, termed bioturbation, are more rapid and complete with the oligochaete worms which act as conveyor belts to deposit subsurface sediments at the soil-water interface. Other organisms (Chironomidae larvae, gastropods, decapods, etc.) also act to alter soil profiles but to a lesser extent. Bioturbation increases exchange rates and solubility of nutrients naturally occurring and from fertilization. Under laboratory conditions, some oligochaete species may rework the entire top 5 cm every 2 weeks (Fisher et al. 1980). In natural conditions these rates are much lower but still highly significant (Krezoski et al. 1978).

Both oligochaetes and chironomid larvae are ubiquitous in fine sediments of virtually all aquatic systems and often become particularly abundant in aquaculture ponds (Bardach et al. 1972). Beyond physical mixing of soils, these taxa pump proportionally large quantities of water into the soil, increasing pore water exchange which ultimately results in increased release of nutrients. Holdren and Armstrong (1980) have reported a direct relationship between silica and phosphorus levels in overlying waters and the presence and abundance of particular chironomid species. Aquaculture systems which promote and establish growth and maintenance of the benthic community should more effectively utilize the nutrients in the system. This concept in aquaculture seems not to have been greatly explored.

In small ponds, mass emergences of adult chironomids may result in heavy losses of nutrients from the system, although again little is known of energy budgets of entire systems to predict this type of flux. This may be most important in tropical aquaculture where chironomid densities often are very high (Oldryd 1964). Further information on nutrient exchange between soils and water as modified by the benthic community of temperate waters has been summarized by Nalepa and Quigley (1980).

Benthic macroinvertebrates can influence fish production in other manners. Several chironomid species feed directly on filamentous algae, as do various gastropods (Cerithidae). These species may compete directly with cultured fish that are also benthic feeders (Bardach et al. 1972; Liang and Huang 1972; Pillai 1972), but the amount of energy lost to the system in this manner is unknown (Pillay 1972). Several physical and chemical methods are used to reduce population of these species (Pillai 1972), but effects on beneficial species have not been shown nor have the effects on nutrient cycling. It has been further shown that certain benthic invertebrates may release growth substances which promote growth of algae (Mundie 1956).

BENTHIC INVERTEBRATES AS A FOOD SOURCE IN AQUACULTURE

Most aquaculture, even low intensity cool water systems, does not rely on natural or added benthic invertebrate populations as a major source of food for fish (Bardach et al. 1972). Seasonality of production and poor knowledge or unpredictability of life cycles have made this impractical. Even under the best of conditions, it is often difficult to establish and maintain the required biomass in either new or ongoing sites. Some elaborate methods of rearing benthic organisms have been attempted with varying success. Pillay (1972) noted one method of rearing larval chironomids in Israel. Shallow pans 1 m in diameter are filled with soil-Asmal, chicken manure, and fish meal. Adult chironomids are attracted by the odor and lay their eggs in the pans. About 200 g/m^2 can be obtained every 2 to 3 days. The success of this method depends on a large stock of wild adult flies being present. When one considers a standard conversion ratio of 10 gm larvae to 1 gm fish, a very large number of pans has to be worked each day to provide sufficient food for even modestly intense aquaculture.

SUMMARY

The greatest contribution of benthic organisms to aquaculture is their ability to modify sediments and enhance release of nutrients. Where algae serve directly to provide a food source for fish, nutrient transfer may be immediate. Benthic bacteria and the larger benthic invertebrates are most important in reworking soils and in facilitating release of nutrients from the soil by assimilating compounds and keeping the top few centimeters in constant movement. Production of fish will be directly proportional to the fertility and type of soils present.

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BIOLOGICAL PRINCIPLES OF POND CULTURE: PHYTOPLANKTON AND MACROPHYTES

by

C. Kwei Lin

Freshwater fish culture has a long history, but an enormous expansion has taken place during the last few decades. The fishes most commonly used in pond culture in warm climates are various herbivorous species, such as carp (grass carp - Ctenopharyngodon idellus, silver carp - Hypothalmichthys molitrix, bighead carp - Aristichthys nobilis, and mud carp Cirrhina molitorella), species of Tilapia and grey mullet (Mugil cephalus). The important species in tropical fish ponds are herbivores, plankton feeders, or omnivores that can thrive on detritus material. Generally, a mixture of two or more species having different feeding habits and stocked in same pond result in greater gross yields.

Although some freshwater fish-farming is carried out in cold temperate climates in Europe and North America, those high-yield intensive cultures (catfish, trout, etc.) require expensive fishmeal. The acute need for animal protein in many underdeveloped tropical countries has turned them to supplies from pond cultured fish. In the tropics, the potential growth rates of fishes under the warmer conditions and extended active growing season provide the most productive fish culture systems (Hickling 1968; Horn and Pillay 1962; Chen 1976). Fish farming in ponds has a long history of empirical development and "green-thumb" expertise, but the scientific investigation and documentation fall relatively short.

PHYTOPLANKTON COMMUNITIES AND SPECIES COMPOSITION IN FISH PONDS

The growth of phytoplankton and aquatic macrophytes is the most critical aspect of fish production in pond culture. The phytoplankton growth and its ecological factors in fish ponds have concerned fish farmers the world over. For example, Lin (1970) stated that many Chinese carp farmers judge the water quality of fish ponds by their color -- the degree of greenness reflects the abundance of phytoplankton. Planktonic algae are food for silver carp as well as for zooplankton, which is food for bighead carp. It also means abundance of dissolved oxygen in the pond produced by phytoplankton. Unfortunately, such expertise seldom provides precise information on species composition, abundance, and related water quality parameters. In recent years, however, many investigations on those aspects have been carried out and documented in scientific periodicals, and are particularly abundant in journals such as Bamidgeh (Israeli) and Hydrobiologia.

Species composition of phytoplankton communities in fish ponds is important because different taxa of planktonic algae present different diet values in various developmental stages of fish or zooplankton. In general, phytoplankton species occurring in fish ponds includes members of Chlorophyta (green algae), Cyanophyta (blue-green algae), Chrysophyta (diatoms and golden brown algae), Euglenophyta (euglenoids), and Pyrrhophyta (dinoflagellates). Literature surveys show that the following genera are most commonly found in warmwater fish ponds (Wiebe 1930; Sreenivasan 1964a,b; George 1966; Vaas and Vaas-van Oven 1959; Zafar 1967; Boyd 1973; Seenayya 1972); Blue-green algae (Microcystis, Aphanozomenon, Anabaena, Oscillatoria, and Spirulina); green algae (Scenedesmus, Pandorina, Ankistrodesmus, Chodatella, Dictyosphaerium, Sphaerocystis, Coelastrum, Tetradron, Pediastrum, Staurastrum, Selenastrum, Oocystis, Closterium, Golenkinia, Kirchneriella); Diatoms (Cyclotella, Fragilaria, Synedra, Nitzschia, and Navicula); Englenoids (Phacus, Euglena, and Trachelomonas); and Dinoflagellates (Ceratium and Gymnodinium).

The phytoplankton species composition in fish ponds may vary from a few to a large number of species. Green and blue-green algae are usually most abundant in warmwater fish ponds. The species diversity concept, developed by Margalef (1958) for phytoplankton, is useful in describing the significance of species abundance in relation to the stability of the phytoplankton community. In general, higher species diversity indicates a greater stability in a given ecosystem (Odum 1971), because the fluctuations in abundance of individual species would have less influence on the entire community than the systems of lower diversity. In most fish ponds, nutrient enrichment by artificial fertilization is commonly practiced in order to increase the fish production (Chen 1976; Hepher 1962; Chiou and Boyd 1974). As a result, the phytoplankton species diversity is lowered in the nutrient enriched system, which leads to a wide fluctuation of total population density. The individual species of phytoplankton in fertilized ponds often undergo rapid cycles of population bloom and massive die-off, and may cause oxygen super-saturation as well as severe oxygen depletion that results in fish kill (Swingle 1968; Boyd 1975). Excessive blooms of blue-green algae frequently occur in nutrient rich water and become the most damaging situation in fish ponds. Blue-green algae produce geosmin, a compound with an earthy-musty flavor and odor, which is excreted

into the water and absorbed by fish, giving them an off-flavor taste (Lovell and Sackey 1973).

The most notorious blooms are commonly formed by members of blue-greens — Anabaena, Aphanizomenon and Microcystis. Those blue-green algae possess buoyant gas vacuoles and accumulate at the surface of a pond during warm, calm weather. The development of blue-green algal scums limits light penetration, lowers CO_2 concentration, and depletes nutrients in surface water. Those conditions lead to massive die-offs and severe depletion of dissolved oxygen following the decay of the dead algae. The photo-oxidation process was also reported as an important factor causing the bloom to collapse (Abeliovich and Shilo 1972; Abeliovich et al. 1974).

After observing many fertilized ponds, Boyd (1979) noticed that the phytoplankton abundance and the species composition in adjacent ponds that receive the same treatment may differ greatly. The causes of these differences are unknown, and therefore no existing management procedure will consistently result in a particular type of phytoplankton community. Although blue-green algal blooms always occur in ponds containing high concentrations of phosphorus and nitrogen, not all eutrophic ponds undergo this event.

To prevent eventual collapse of blue-green algal blooms, destratification of the water column by mechanical means has been proven to be effective (Swingle 1968; Zarnecki 1967). The most fundamental way of preventing excessive blooms is through manipulating nutrient levels, keeping certain critical elements at a steady-state limiting situation. Recently, as experienced on nutrient enrichment in a whole lake involving variation of the N/P ratio shows a new insight in changing dominance between blue-green and other types of phytoplankton (Schindler 1977). Nutrient bioassay might provide a rapid, economical means to investigate the nutrient requirement for phytoplankton species composition and abundance desirable in fish ponds. The nutrient bioassay techniques have been widely used in predicting phytoplankton production in relation to eutrophication in natural waters. The systems analysis and numerical models that have been developed for eutrophication in natural waters may provide useful managerial procedures for fish ponds.

The food and feeding habits of freshwater fishes have received much attention (Alikunhi 1952, 1958; Singh 1958, 1961; Das and Moitra 1955; Gupta and Ahmad 1966; Vaas and Vaas-van Oven 1959). Philipose (1960) has reviewed the role of phytoplankton in inland fisheries. The algae commonly used are diatoms, some members of blue green algae, and a few greens. The observations show that diatoms are readily digested in fish stomach (Fish 1951; Evans 1960). Tay (1960-61) showed that Anabaenopsis was more readily digested than Anabaena. It is suggested that no further studies on food value of individual phytoplankton components rather than populations as a whole are needed. In spite of considerable work done on the utilization of algae by fishes, little work has so far been done on the effect of feeding selectivity by fishes on sizes and the nutritious value of algae.

PRODUCTIVITY

Since most fish raised in warmwater ponds in underdeveloped countries are dependent largely upon natural foods, the fish production is closely related to the levels of primary productivity of aquatic plants -- phytoplankton and macrophytes. Boyd (1979) illustrated that in fertilized ponds stocked with sunfish (Lepomis spp.) and largemouth bass (Micropterus salmoides) phytoplankton represents the base of the food web which culminates in fish production. The production of sunfish is almost directly related to concentrations of particulate organic matter in the ponds (Smith and Swingle 1938; Swingle and Smith 1938). In those fish ponds, the phytoplankton biomass usually comprises most of the particulate organic materials. Maleck (1976) reported that fish yields increased in African and Indian lakes with increasing gross photosynthesis. Production of Tilapia aurea also depends greatly upon plankton density (Almazan and Boyd 1978). Sreenivasan (1964a,b) reported that primary productivity in three tropic Indian lakes were 0.46, 2.9, and 3.8 g C/m^2/day and the fish production was 5.3, 31.6, and 75 kg/hr respectively.

Since managed fish ponds are often fertilized, their nutrient concentrations are generally higher and phytoplankton productivity greater than the average natural waters. Boyd (1973) reported that chlorophyll concentrations in a series of fertilized ponds averaged about one order of magnitude greater than those in the unfertilized ones. In Israel the chlorophyll concentrations in fertilized ponds reach between 103 and 212 µg/L, while the values in unfertilized ponds ranged from 8.8 to 115 µg/L (Hepher 1962). Boyd (1973) also observed that chlorophyll values in fed catfish ponds averaged 102 µg/L, as stimulated by the nutrient released from the feed.

Gross phytoplankton productivity is closely related to the fertility of the ponds. Hall et al. (1970) reported that primary productivity was 10-15 times greater in fertilized ponds than in unfertilized controls. In Israeli ponds (Hepher 1962), the average productivity ranged from 3.3 to 6.4 g C/m^2/day and the conversion rate to fish production was 1.3-2.3% C. In most fish ponds, rates of gross productivity are highest near the surface water and decline rapidly with depth because the dense phytoplankton standing crop reduces light penetration. The compensation point at which the amount of oxygen produced by photosynthesis equals the amount consumed by respiration is extremely shallow. Boyd (1973) recorded that the depth of the compensation points at the Auburn experiment ponds were 0.4-0.75 m, and Hepher (1962) observed them usually at 0.4 m in Israeli ponds. It is concluded that nutrient enrichment of ponds increases phytoplankton production in the upper layers of water and decreases productivity in deeper water. Therefore, excessive fertilization may lower productivity per unit area over the pond.

MACROPHYTES AND BENTHIC ALGAE

Aquatic macrophytes which commonly occur in fish ponds include macroalgae, mosses, ferns, and flowering vascular plants. They appear in various growth forms -- submersed, floating, or emergent. The biology of aquatic macrophytes has been a subject of much investigation and reviewed in great detail by Gessner (1959), Sculthorpe (1967), and recently Hutchinson (1975). Macrophytic algae include those

species dwelling in the bottom, e.g., Chara and Nitella and species of filamentous algae which form mats floating on the surface, such as Spirogyra, Cladophora, Rhizoclonium, and Pithophora. Most common vascular plants are species of Eichhornia, Potamogeton, Ceratophyllum, Myriophyllum, Elodia, Najas, and Lemna. Ferns, such as Azolla and Salvinia, are common free floaters.

Macrophytes normally occur in ponds with relatively transparent waters. While floating macrophytes absorb their nutrients from the water column, the rooted ones can use the nutrients from both the water column and sediments (Boyd 1971; Denny 1972; Bristow 1975). Boyd (1979) reported that relatively unproductive fish ponds may support luxurious macrophyte growth due to their ability to use nutrients from the mud. The potential for macrophyte production is greater in hard water than in soft, acid water. In hard water the macrophytes often cause calcium and magnesium to precipitate in colloids.

Occurrence of macrophytes is normally undesirable in managed ponds because they compete for nutrients with phytoplankton, interfere with fish mobility and feeding, and interfere with fish harvest. The most common and serious problems in a pond result from extensive growth of floating macroalgae and higher plants, such as Eichhornia, Lemna, and Azolla because they prevent light penetration causing light limitation for phytoplankton growth. Dobbins and Boyd (1976) reported that macrophyte growth was an important factor in causing unpredictable plankton production, and thus presented a difficult management procedure in fertilizing the ponds. However, there are occasions where aquatic macrophytes in fish ponds become beneficial. Little (1979) gave an extensive review on the utilization and nutritional value of aquatic plants for fish culture throughout the world. The best example is grass carp culture ponds (Chen 1976), where the fingerlings feed on Lemna and mature fish on a large variety of aquatic and even land vegetation. In semi-managed ponds, the aquatic macrophytes can also be beneficial because they harbor a large variety of attached invertebrate fauna such as snails and gammarids which are sources of food for certain fish.

Although macrophyte growth increases with increasing nutrient concentrations, it is often inhibited by turbidity (Spence 1964; Boyd 1971). Smith and Swingle (1941) suggested that inorganic fertilization of ponds often triggers plankton blooms which shade the bottom and prevent macrophyte growth. The maximum depth at which macrophytes occur exhibits a linear relationship with Secchi disc transparency (Hutchinson 1975). Boyd (1975) found that growth of underwater macrophytes was inhibited at depths greater than twice the Secchi disc visibility in ponds in Auburn, Alabama.

Benthic algae have seldom been reported to play a major role as fish food in pond culture. Although microscopic diatoms have been reported as an important food source for detritus feeders such as Tilapia mossambica in tropical lakes (Bowen 1978, 1979), in most fish ponds the dense phytoplankton growth often prevents penetration of light to the bottom of the ponds. Therefore, benthic algae growth is light limited. To fully utilize benthic algae for the culture of Tilapia it may be desirable to design ponds shallow enough to promote the healthy growth of benthic algae. A benthic algal bed has been successfully used for milkfish culture in Taiwan (Ling 1966). There the good growth of benthic algae is responsible for the success of milkfish farming. The benthic algae usually consist of blue-green algae (Oscillatoria, Lynghya, Phormidium, Spirulina, and Micrococcus), and diatoms (Navicula, Mastogloia, Stauroneis, Amphora, and Nitzschia).

RESEARCH NEEDS

As a result of the brief literature review, the following aspects of phytoplankton ecology require further knowledge and research in freshwater fish culture ponds:

1. The environmental conditions governing species composition and succession, particularly control of blue-green algae blooms.
2. The desirable phytoplankton species composition, biomass, and productivity for sustaining an optimal yield of selected species of fish.
3. The relationship between nutrient ratio (N:P) and dominance of phytoplankton species.
4. The nutritional value of phytoplankton for herbivorous fish: protein, carbohydrate, and lipid content of phytoplankton.
5. Phytoplankton response to fertilization (organic and inorganic).
6. Nutrient assimilation capacity of a phytoplankton community, with an emphasis on its utilization of ammonia released by fish, and anaerobic decomposition of organic matter.

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BIOLOGICAL PRINCIPLES OF POND CULTURE: ZOOPLANKTON

by

Marlene Evans

STATE OF THE ART OF ZOOPLANKTON IN AQUACULTURE SYSTEMS

The role of zooplankton in aquaculture systems has been investigated to various levels of precision. The crudest is simply a faunal list of zooplankton inhabiting waters that are used or have the potential for being used to rear fish. In general, most of these studies are not at the level of sophistication that characterizes oceanographic and limnological studies conducted in Europe and North America.

Survey Studies

Survey studies have been conducted to determine the suitability of a water body for the introduction of a particular fish species. For the most part, these studies have been conducted in large bodies of water such as lakes, reservoirs, and rivers. Given the size of these systems, little or no management of the water body was intended as part of the stocking program. The major decision regarding the suitability of a water body for the introduction of a fish species has been its physical and chemical characteristics. However, most such studies have determined the major floral and faunal components.

In India, several studies have investigated the hydrobiology of various waters which have the potential for fish culture. Ganapati and Chacko (1951) studied one lake, two reservoirs, and four rivers in Madras State, India (elevation approximately 7,000 ft.). Kodaikanal Lake supported a rich plankton population. English carp (Carassius carassius) and baril (Barilus gatensis) were successfully introduced into the lake and formed part of a fishery. In addition to these fish, the fishery was based upon minnows, a few Mahseer (Barbus tor), and murrels (Ophicephalus gachua). Conversely, Pambar Reservoir and Berijam Reservoir were poor in plankton. English carp and rainbow trout had been introduced into these reservoirs although without success. The reason for this failure was not investigated but may have been related to low plankton production. While rainbow trout previously had been successfully introduced into certain rivers, they were decimated by overfishing and heavy otter predation. The authors concluded that the rivers investigated in their study and the three lakes could be used to culture food and game fish. A total of five genera of rotifers, two genera of cladocerans (Daphnia, Ceriodaphnia), and two genera of copepods (Microcyclops, Eucyclops) were observed in the seven bodies of water. Zooplankton occurred more commonly in Kodaikanal Lake and Berijam Reservoir, although not enough information was provided to interpret the ecological significance of these differences.

Chacko and Ganapati (1952) conducted a hydrobiological survey in the Surula River (elevation 4,850-6,000 feet) in India and concluded that the river was suitable for the introduction of rainbow trout. Zooplankton included three genera of protozoans (Holophyra, Lacrymaria, Ulvella), six genera of cladocerans (Acroperus, Alonella, Anuraea, Ceriodaphnia, Diaphanosoma, and Simosa), one ostracod (Stenocypris), and three rotifers (Rotifer, Rattulus, Pedalion); copepods apparently were not collected.

Huq and Sirajul Islam (1977) conducted a survey of man-made ponds in a village in Bangladesh to determine their productive capacity, current use, and reasons for underutilization for aquaculture. The study was an opinion survey of the villagers and provided little data on the physical, chemical, and biological properties of the water. However, the study is noteworthy because, although the ponds were located within a relatively small distance of each other, they apparently differed in their abilities to support fish growth. About 61% of the ponds supported good fish growth while about 12% of the ponds did not.

In Africa, Munro (1966) conducted a limnological survey of Lake McIlwaine, comparing this Rhodesian lake with other lakes in Central South Africa. Lake McIlwaine is utilized as a sport fishery and also supports a gill net fishery. The lake is mildly polluted by sewage and has an abundant plankton population. The author reports ten species of rotifers, six species of cladocerans, and three species of copepods in addition to a littoral cladoceran and ostracod, a Chaoborus species, and a species of the coelenterate Limnocnida. No estimates were made of zooplankton standing stocks although some seasonal percent composition data were presented.

The state-of-the-art for surveying water bodies for their potential use in low-intensity aquaculture systems is not well developed. The present approach consists of surveying a water body with respect to its physical and chemical characteristics, with relatively little attention addressed to the indigenous biota.

However, for fish to be successfully introduced into a stream, river, or reservoir, the biota must be present in sufficient quantities and types to satisfy the nutritional requirements of the fish throughout its life. Zooplankton-consuming fish must be presented with a sufficient array of forms to ensure its survival, healthy growth, and successful reproduction.

Survey studies should contain detailed information on the composition, abundance, and seasonality of zooplankton. All too often, zooplankton data are reported simply as species lists based on single date collections. Survey studies also should provide some estimate of secondary production so that the value of a body of water for fish production can be estimated. Similarly, production estimates are necessary to estimate appropriate stocking programs.

Many studies have been conducted in developing regions of the world, providing information on the ecology of tropical water bodies. For example, Lewis (1978) conducted an excellent study of the dynamics and succession of phytoplankton in a tropical lake in the Philippines. Zooplankton grazing activity (seven species of rotifers, three species of cladocerans, and two species of copepods) was estimated and found to remove only a small percentage (< 7%) of the daily primary production. Systems such as these may be particularly suitable for the introduction of phytophagous fish. Matsumura-Tundisi and Tundisi (1976) studied Broa reservoir in Brazil. Populations were more stable in the cold dry season than in the warm rainy season. The reasons for this were not investigated. Rotifers were the most abundant zooplankter (77.6%), consisting of 15 species. Cladocerans consisted of three major species and accounted for 13.6% of the zooplankton. Copepods were the least abundant (8.7%) taxonomic group, consisting of six species.

Zooplankton as Indicator Species

A number of researchers have observed that zooplankton composition varies as a function of the physical, chemical, and biological characteristics of the water. Because of this, zooplankton have often been used as indicators of certain trophic conditions of water bodies. Arora (1966) studied rotifers as indicators of the trophic natures of two lakes, a tank, and an oxidation pond in Nagpur, India. Gorewara Lake was considered oligotrophic, Sakardhara Lake was mildly polluted, while Jumma Tank was more strongly polluted with sewage and industrial effluent. Thirty-six species of rotifers were observed in this study. Considering the two lakes and the tank, the highest density (1,992/L) of rotifers was observed in Jumma Tank while the lowest (< 9/L) was observed in Gorewara Lake. Populations were lowest in July and August, possibly due to the turbidity of the water during these monsoon months. Brachionus falcatus, B. Forficula, B. quadrilidentatus, and Tetramastix opoliensis were characteristic of the clear waters of Gorewara Lake (maximum rotifer density 245/L) while Filinia terminalis, Epiphanes macrurus, Asplanchna intermedia, Pedalia intermedia, B. angularis, and B. calyciflorus were characteristic of the polluted waters of the aeration pond. Rotifer densities in this pond attained a maximum of 14,600/L.

Zooplankton Composition as Affected by Planktivorous Fish

Zooplankton composition is affected by the presence of size-selective planktivorous fish which remove the larger components of the zooplankton. Classic studies were conducted in fish ponds by Czechoslovakian researchers in the 1960s. Straskraba (1967) showed that, in the absence of fish predators, the zooplankton community in the littoral region of fish ponds was dominated by the large Simocephalus vetulus and Daphnia pulex. However, when predatory fish were present, these zooplankton were replaced by the smaller Chydorus sphaericus and other euplanktonic cladocerans. Postolkova (1967) observed that the standing crop of zooplankton was greater inside a fenced portion of the pond than outside: fish predators were excluded by these enclosures and thus were unable to reduce the standing stock of zooplankton. In an earlier study, Straskraba (1963) determined that phytoplankton production was lower in the littoral region than in the open region of the pond due to macrophyte shading. Phytoplankton producton was not sufficient to support the littoral zooplankton community. The author concluded that the growth of macrophytes should be discouraged in fish ponds.

Zooplankton and Fish Stocking

Zooplankton composition in a water body also is a function of the rate of fish stocking. Marvan et al. (1978) described a number of south Bohemian ponds stocked with various numbers and sizes of fish. Ponds with low fish stocks (700/ha) were dominated by the cladocerans Daphnia pulicaria and D. longispina. Polytrophic ponds with high concentrations of fish (about 20,000/ha with small fish and fry) were dominated by the smaller Bosmina longirostris, Ceriodaphnia affinis, Diaphanasoma brachyurum, cyclopoida, and rotifers in addition to some D. longispina and D. pulicaria.

While it is well-known that planktivorous fish affect zooplankton composition in a water body, many questions have yet to be answered. Predation rates of fish on zooplankton have not been well-qualified and are of particular relevance to aquaculture systems. Strategies by which zooplankton avoid predation have been investigated in a number of natural systems and include morphological (increased transparency) and behavioral (vertical migration) adaptation. However, more work must be done in aquaculture systems. How do zooplankton populations compensate for grazing? Laboratory experiments and certain field studies indicate that, under such stresses, zooplankton fecundity increases. However, the birth rate can increase only to a certain level beyond which losses due to predation cannot be compensated for and the population crashes. Grazing may have a greater effect on copepods which tend to have somewhat longer developmental times than cladocerans and rotifers; longer development time to the adult increases the probability that development will not be complete before predation occurs. In addition, as copepods reproduce sexually, the population must remain dense enough for males and females to locate one another. Conversely, cladocerans and rotifers reproduce parthogenetically and probably can withstand greater grazing pressures. There is the need for more aquaculture research at the theoretical level on

zooplankton-planktivorous fish interactions, particularly with regard to predation avoidance mechanisms and the ability of the zooplankton population to withstand heavy grazing pressure.

Zooplankton and Fish Yield

Several researchers have suggested that there is a strong correlation between primary productivity, zooplankton productivity, and fish yield. This has been confirmed experimentally for phytoplankton-fish production relationships by a number of researchers including Hall et al. (1970) and Goodyear et al. (1972).

Das and Upadhyay (1979) studied the qualitative and quantitative fluctuations of plankton in two Kuman lakes in India. Nainital Lake (altitude 1,938 m) was highly eutrophic and polluted: plankton densities ranged from 0.9 to 1.8 mL/m^3 and formed the major food for the larvae, fry, and fingerlings of the Mahseer fish population. Oligotrophic Bhimtal Lake (elevation 1,376 m) with low plankton populations (0.08-.44 mL/m^3) apparently did not support significant commercial fisheries. In both lakes, population maxima occurred in spring (March) and after the monsoon (August).

Sreenivasan (1964) conducted a limnological study and estimated fish yield in three upland lakes in Madras State, India. Kodaikanal Lake had low primary production averaging 0.46 $gC/m^2/day$. Zooplankton (50-120 ind./L) were dominated by copepods, cladocerans, and the rotifers Brachionus sps. and Eubranchipus. Fish production (Carassius carassius and Cyprinus carpio) was also low (5.3 kg/ha). In comparison, Yercaud Lake had a higher average primary production rate (2.9 $gC/m^2/day$) and zooplankton were more abundant (80-600 ind./L). Copepods, cladocerans (Aneuraea), and rotifers (Brachionus, Eubranchipus, Asplanchna) were the dominant taxa. Fish yield (C. carpio and some Tipapia mossambia) was high (31.6 kg/ha). Ooty Lake, polluted by sewage input, had the highest average primary production rate of 3.8 $gC/m^2/day$ and abundant (42-12,280/L) zooplankton populations. Dominant zooplankton included copepods, cladocerans (Aneuraea, Daphnia), and rotifers (Monostyla, Triarthra, Eubranchipus, and Brachionus). Fish yield was highest, exceeding 75 kg/ha.

Gophen and Landau (1977) studied the trophic interaction between zooplankton and the sardine Mirogrex terraesanctae in Lake Kinneret, Israel. They found that the biomass and productivity of caldocerans was higher (30-170%) in 1973 and the first half of 1974 than the average for 1969-1972. This increase in food resources apparently contributed to an increase in the sardine population in 1974-1975. Juvenile sardines grazed heavily upon the zooplankton, reducing both the cladoceran population and the adult female copepod population. Females compensated for this decrease in numbers by increased fecundity.

Schroeder (1973) investigated factors affecting feed conversion ratios (kg feed supplied:kg fish yield) in fish ponds in Israel, and found that there was a strong correlation between feed conversion ratio and zooplankton standing stock at zooplankton densities of 0.1 to 1.1 mg dry weight/L. Within this range, natural feed was the major factor governing the efficiency with which supplemental food was used by fish. At higher zooplankton densities, the feed conversion ratio remained unchanged (approximately 1.8), suggesting that there may have been excess natural food in the pond. Fish were stocked at densities of 1,000-5,000 kg/ha. Zooplankton were dominated by rotifers, Cyclops, and the cladoceran Moina. Schroeder also determined that zooplankton standing stocks in fish ponds were affected by flushing rates, with population density decreasing with increased flushing.

In a later study, Schroeder (1978) showed that ponds fertilized with cow and chicken manure, and with nitrogen and phosphorus fertilizers, could produce 15-30 kg/fish/ha/day (common carp, Tilapia, silver carp). Fish obtained half their food supply from organisms greater than 37 mm in size and the remaining half by directly consuming smaller particles. These smaller particles consisted of bacteria and protozoans. The addition of inorganic fertilizers alone increased primary productivity, while the addition of manures along with those fertilizers did not increase primary productivity of plankton standing stocks. The highest fish yields (32 kg/ha/day) were obtained when fertilizers and manures were added, while yields (10-15 kg/ha/day) were lower when only fertilizers were added. Schroeder provided some information on plankton composition and zooplankton production rates in his experimental ponds. He stated that young water had low densities of zooplankton which were dominated by rotifers and were followed by a pulse of Moina. Old water contained copepods (mainly Cyclops). In addition, he conducted enclosure experiments and observed at the end of a week that zooplankton retained in fine net enclosures were about five times more abundant than zooplankton in ambient waters. This suggests that fish predation on the zooplankton was intense.

These aquaculture studies confirm what previously has been demonstrated in other freshwater systems: there is a good correlation between primary production, zooplankton standing stock, and fish yield. However, many areas require further investigation. For example, what are zooplankton production rates in pond aquaculture systems? How do these rates vary with primary production and allochthonous inputs? What is the transfer efficiency between various trophic levels? What are the major energetic pathways? What are the seasonal dynamics of primary and secondary production and how do these relate to fish growth and yield?

Zooplankton in Polyculture Systems

Many aquaculture ponds are used to rear more than one species of fish. However, the success of such a polyculture system depends upon the appropriate combination of noncompeting species. For example, two phytophagous fish species would be a poor choice in a polyculture system while a phytophagous fish may be successfully reared with a particulate-feeding fish. Consequently, there has been a great deal of research investigating fish feeding habits in polyculture systems, including the role of zooplankton in fish diet. In addition, there has been some work on the effect of various combinations of fish species and standing stocks on the zooplankton community. Fish can affect zooplankton either directly through grazing or indirectly by modifying the ecological balance of the pond. For example, a fish species may through various mechanisms contribute to the growth of an algal form

which is a good food source for one species of zooplankton but not another.

Grygierek (1973) investigated the influence of phytophagous fish and the common carp on zooplankton populations in several experimental ponds in Poland. He found that increased carp density resulted in an increase in the abundance of zooplankton, more rapid seasonal changes in numbers, and a shift in species dominance from the large Daphnia longispina to the smaller Bosmina longirostris and Ceriodaphnia quadrangularis. In pond systems with the same number of carp fingerlings and phytophagous fish (common carp, grass carp, silver carp, bighead carp), the total number of zooplankton was reduced. However, the larger D. longispina and Moina rectirostris were relatively more abundant, although the actual composition was dependent upon the common carp-phytophagous carp combinations. Grygierek proposed that two factors were important in affecting zooplankton composition within the ponds. One factor related to differences in the size-selective feeding behavior of the various carp species. Grass carp were highly size-selective in their feeding while the common carp was slightly less selective. Silver carp and bighead carp fingerlings fed on zooplankton but were not as highly size-selective.

The second important factor in Grygierek's study was the effect of fish composition on the microbial and phytoplankton communities. Both communities tended to be more abundant in ponds containing phytophagous fish and common carp than in ponds containing only common carp. In ponds with bighead carp, blue-greens were abundant, while diatoms were abundant in ponds containing only common carp. Differences in zooplankton composition between those ponds may have been related, in part, to differences in the microbial and phytoplankton communities which provided food resources to these invertebrate grazers.

Spataru (1977) studied the gut contents of silver carp and trophic relations to other fish species in a polyculture system. Four types of ponds were studied, consisting of a two-factor combination of fertilizer (fluid manure, fluid manure + sorghum) and treatment (storage pond, pond allowed to dry out following harvest). The poorest growth was obtained in ponds which were fertilized with manure only and allowed to dry out at the end of the summer. Best growth was obtained in ponds which were fertilized with manure and sorghum and which maintained a planktonic community throughout the year. In these ponds, there was excellent growth of the algae Scendedesmus, the preferred food of the silver carp, and sufficient benthic and detrital matter was present for Tilapia. In addition, common carp grew well on sorghum. This study suggests the importance of maintaining an ecologically balanced community even with supplemental feed. However, the nature of this ecological balance, including the zooplankton community, was not investigated.

An additional interesting observation reported by Spataru (1977) is that, while silver carp consumed zooplankton such as Rotaria and Brachionus, these rotifers passed through the gut unharmed. No additional information was provided on zooplankton composition and abundance in these ponds.

Hiatt (1944) investigated feeding habits of mullets, milkfish, and ten pounders in Hawaiian ponds. Mullets and milkfish are herbivores, feeding on similar phytoplankton. Zooplankton apparently were not consumed, possibly because of their larger size. Ten pounders consumed shrimp and mosquitofish (a secondary consumer according to Goodyear et al. (1972)). Hiatt suggested that fish yield in polyculture systems could be improved by adding ten pounders while competition between milkfish and mullet probably reduced yield.

Cremer and Smitherman (1980) studied the food habits of silver carp and bighead carp in ponds in Alabama. Silver carp consumed primarily phytoplankton and grew successfully in cages. There was no difference in silver carp growth between ponds receiving and not receiving artificial feed. Conversely, bighead carp consumed large particles, including large quantities of zooplankton and detritus. Zooplankton food items included copepods, cladocerans, ostracods, rotifers, mites, amphipods, and chironomids. Bighead carp grew poorly in cages and responded well to artificial feeding.

More questions require further investigations in order to understand the dynamics of polyculture systems. Competition between phytophagous fish and herbivorous zooplankton has not been investigated and may affect fish yield. The effect of several fish species on zooplankton composition and abundance have been examined only superficially. For example, a planktivorous fish will consume only zooplankton which are of the appropriate size and palatable. Such predation will affect the competitive balance between zooplankton species, but in ways that are not well understood. For example, will the successful competitor be of a form that is a food source for another fish in the pond or will it be a form that competes with fish? Alternately, the form may be beneficial in other ways, either by serving as an energy source for invertebrate predators which are consumed by fish or by altering the phytoplankton community to forms that are more suitable to the phytophagous fish.

Zooplankton and Pond Balance

Several studies have indicated the importance of maintaining a balanced fish population in pond ecosystems. As stated previously, Spataru (1977) observed that fish yield was higher in ponds which did not dry out over winter and which could maintain a natural assemblage of organisms, while growth was poorer in ponds which do dry out resulting in the disruption of the natural succession. In ponds where intense algal blooms develop, the production of large amounts of ammonia from decaying algae can produce diseased fish (Seymour 1980). By properly managing ponds so that algal growth is not excessive and so that grazing rather than nutrient depletion causes a reduction to phytoplankton standing stocks, such occurrences may be avoided.

Laventer et al. (1968) studied a series of fish ponds in Israel on means by which fish production could be increased. Pond water level decreased over the winter and increased between January and March with the spring rains. Algal standing stocks (primarily diatoms and greens) increased at the latter period. This was then followed by an increase in crustacean

abundance. Laventer stated that this was the best time to add carp to the ponds although carp did not feed on plankton. Since chironomid larvae, the main food of the carp, did not appear in the pond until April, it is not clear what organisms were consumed by the carp at this time. Nevertheless, the particular balance which was established in the pond in mid-spring (abundant crustacean populations) was ideal for carp growth.

Overview of Plankton Ecology and Fish Yield in Aquaculture Systems

The literature review to this point has discussed the composition and production of primary, secondary, and tertiary trophic levels of organisms in relation to fish production. In low- and moderately-managed systems, there is a good relation between primary production and fish yield. The zooplankton abundance and compositon have been measured less frequently in these systems and they are clearly affected both by primary production and by fish standing stocks.

Primary production in pond systems can be increased by the addition of chemical fertilizers to a point where increased addition of chemical fertilizers does not result in increased algal growth. This may be due to limiting of other nutrients or to self shading.

Two mechanisms exist to further increase fish yield. Where ponds are stocked with fish that feed on large organisms such as zooplankton and benthos, diet can be supplemented by the addition of pellets, grains, offal, and other food items. Conversely, in ponds which contain filter-feeding fish which can handle particles only a few tens of microns in size, increased yield can be accomplished by adding manures so that a large microbial community is established.

The role of zooplankton in pond systems has not been well-quantified and will vary as a function of allochthonous inputs and the abundance and composition of fish. Relatively little work has been done to estimate zooplankton production in various aquaculture systems. Korinek (1966) estimated production of adult female Daphnia pulicaria in a carp pond in South Bohemia while Gophen and Landeau (1977) estimated zooplankton production in Lake Kinneret. Techniques for estimating zooplankton production are well developed and production estimates have been made for a variety of waters (Comita 1972; Burgis 1964; Hall et al. 1970). Although procedures for estimating zooplankton production are relatively simple, they do involve more intensive sampling than primary production estimates. This probably is the major reason that both zooplankton and benthos production have been estimated less commonly than primary production.

Relatively few studies have addressed other aspects of zooplankton biology (growth, respiration, excretion, fecundity) in aquaculture systems. Gophen (1976a,b) investigated the physiology of Mesocyclops leuckarti and Ceriodaphnia reticulata in Lake Kinneret. O'Brien and Vinyard (1978) studied polymorphism in Daphnia carinata in two south Indian ponds, along with the effects of invertebrate predators. These research studies have provided valuable contributions to the understanding of zooplankton and indicate further areas of basic zooplankton research in low intensity pond and lake aquaculture systems.

Zooplankton as First Food for Fish Fry

The role of zooplankton in intensive pond systems is not well-understood, particularly for adult fish. However, in such systems where large numbers of fry are reared in nursery ponds, the importance of zooplankton as a first food for many species of fish is well-recognized. Many intensively managed systems grow zooplankton to improve the survival of the early developmental stages of fish. The rotifer Brachionus and the brine shrimp Artemia are the most commonly reared food items (Stickney 1979) although marine researchers have experimented with brackish-water harpacticoids (Kahan 1979). Since such copepods are benthic, their usefulness in pond systems would appear to be limited to bottom-feeding larvae.

Some researchers have investigated the biochemical composition of zooplankton, although much more work is needed in this area. Scott and Baynes (1978) showed that the biochemical composition of the rotifer Brachionus plicotalis was affected by starvation. Although rotifers did not decrease in size, they did decrease in weight under low-food conditions. More importantly, there was a reduction in lipid, protein, and carbohydrate levels. Thus, in the early stages of fish's life when larval growth is rapid, it is vital not only that the proper number and size of zooplankton be present as food items, but that these zooplankton contain the appropriate nutrients. Farkas et al. (1977) demonstrated that the carp Cyprinus carpio can develop nutrient deficiencies when their diet lacks essential fatty acids.

Methods for Improving Zooplankton Harvest

Paulsen (1977) developed an apparatus for collection of invertebrates from ponds. It essentially consists of pumping water from the pond through a series of filters ranging in size from 75 to 1,600 µm for use in collecting food items for fish. Since the device did sort the invertebrates by size, the smaller fractions could be used to feed fish fry while the larger fractions could be used to feed fish which consume benthos and/or other large particulates. The system has potential use in ponds with high flushing rates which tend to deplete their plankton population (Schroeder 1973).

Green and Merrick (1980) developed a covered pond system for improving the survival of fry. Although gold and silver perch fry will consume pellet feeds, growth is better when they are fed plankton. However, in some systems, invertebrate predation on plankton decimates the population and leads to poorer fry growth in these nursery ponds. Green and Merrick developed their system to exclude invertebrate predators (dragonflies) which entered the pond and preyed heavily upon the plankton. An added benefit to their system was that diel temperature fluctuations were reduced and pond waters did not reach the temperature extremes observed in more open systems. A final advantage not mentioned by the authors was the probable reduction in evaporation rates. Lowering of pond levels has been a problem in a number of Israeli studies (Spataru 1977).

Invertebrate Predators on Zooplankton

Zooplankton are subject to predation not only by fish and dragonflies but also by a variety of invertebrates living in pond systems. Clady and Ulrickson (1968) reported that hydra consumed large numbers of Daphnia pulex in a tank system. Because the cladoceran population was abundant, the hydra increased in numbers. After the zooplankton population was decimated, the hydra attacked young bluegill fry.

Zooplankton as Predators on Fish Larvae

Some zooplankton prey upon fish larvae. Sukhanova (1968) demonstrated that silver carp larvae were attacked by the cyclopoid Acanthocyclops vernalis in Indian ponds. Cyclopoid predation occurs commonly and has been reported by a number of fresh water (Davis 1959; Hartig et al. 1980) and marine (Lillelund and Lasker 1971) researchers.

Zooplankton as Parasites

Certain species of copepods are fish parasites, notably Ergasilus, Argulus, and Lernaea. These parasites damage the fish either directly by disrupting tissue or secondarily through infection (Stickney 1979; Khalifa and Post 1976). Problems are particularly severe in storage ponds where the high density of fish promotes the rapid dispersal of the parasite (Lahav et al. 1964).

CONCLUDING REMARKS

This report reviews the known role of zooplankton in various aquaculture systems. It suggests areas of future research needs. In some aquaculture systems, where an adequate descriptive data base exists, relatively sophisticated studies can be conducted to investigate processes and test hypotheses. Conversely, in areas where aquaculture programs are in the early stages of development, more basic research on the limnology of pond ecosystems must first be conducted.

The literature review focused on studies conducted outside North America and Europe although some such studies are discussed when comparable studies have not been conducted in less developed regions of the world. This review includes a range of water bodies which support or have the potential for supporting a freshwater fishery: lakes, reservoirs, and ponds which have been affected to varying degrees by human activity (primarily eutrophication). Apart from North American and European studies, most of the published extensive aquaculture research has been conducted in India and Israel. Both countries have well-developed aquaculture programs (Pillay 1979) and publish much of their research results in English in the western literature. Conversely, although China has an extensive aquaculture program (Pillay 1979), much of its research has not appeared in the western literature. Japan also supports a highly developed aquaculture program and current research is published in English in the western literature. The Japanese aquaculture projects are highly intensive, involving large capital investments and high maintenance costs. Because this report is primarily concerned with cultivation systems which do not necessitate large investments and maintenance costs (extensive systems), a review of the Japanese literature was not included.

This review provides an overview of aquaculture systems in various parts of the world. Much of the aquaculture research has not been abstracted and computer searches generated a relatively small number of citations. Most of the literature was located through more traditional means of literature search. Some articles have been published in journals and reports which are not held by the University of of Michgan library and were not located by the time of this writing. As a consequence, the bibliography consists of two parts; one part contains articles which were read and included in the state of the art review, while the other part contains a list of additional reading.

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BIOLOGICAL PRINCIPLES OF POND CULTURE: FISH

by

James Diana and David Ottey

Production of fish biomass in pond culture systems is regulated by three parameters: stock density, mortality, and growth in individual weight (Backiel and LeCren 1967, 1978; Chapman 1971). These parameters are related through mechanisms of biotic interactions and their physico-chemical environments (Fry 1947, 1971; Kerr 1980; Werner 1980), as previously shown in this document. For many cultured fish species, pond management for maximization of biomass production and standing stocks remains limited by knowledge of the ecological principles of the systems. The mechanisms relating stocking density, mortality, and growth are therefore key considerations of this study.

Growth relations with density, including definition of specific ecological mechanisms, may well be the most effective area for research on pond culture. Reasons for emphasis on density-dependent mechanisms of growth rather than on mortality or density-independent processes include: 1) A vast number of studies has dealt with nutrition and dietary effects on growth. 2) Stock densities have more generally defined and stronger effects on growth than on mortality in culture systems (Backiel and LeCren 1978). The plasticity of individual growth in exploited populations in fish is well-documented, and indicates the importance of density in control of growth. 3) Within a cohort, growth and mortality are more commonly controlled by density-dependent rather than density-independent processes (Larkin 1978). This may be particularly germane as intensively cultured pond systems can be controlled for stocking rates, physico-chemical factors, and food or nutrient inputs. 4) Evaluation and quantification of mechanisms of density effects on growth will provide characters for genetic stock manipulation explicit to culture situations and species. Genetic control of growth in fish is well established, but selection of growth-related traits requires physiological-bioenergetic analyses (Weatherley 1976). 5) Many empirical and mechanistic (bioenergetic and optimum foraging) models exist on growth relation to density and ration (e.g., Ware 1975, 1978; Paloheimo and Dickie 1965, 1966; Kerr 1971a, 1971b; Sperber et al. 1977). Additionally, the balanced energy equation for metabolism and growth (Winberg 1956) provides a powerful paradigm for evaluation and analysis of factors affecting growth (Warren and Davis 1967; Webb 1978).

Unfortunately, the analysis of mechanisms and development of appropriate models for species and situations of tropical pond culture are yet in their infancy. The major purposes of this synopsis are to examine recent research effort in pond culture principles, and to provide schemes for describing and examining density effects on growth.

GUIDELINES FOR STUDY

Recent (1976-80) aquaculture and fish biology literature was reviewed while emphasizing ecological and physiological mechanisms governing reproduction, growth, mortality, and recruitment to harvest of fishes commonly cultured in tropical ponds. The reference search has thus been autecological in perspective, although some of the most important processes, such as interspecific competition and facilitation of trophic efficiency, are synecological in nature. The multidisciplinary approach taken by this CRSP research group required an interactive, integrated scheme for relating principles of the systems, but the extensive tropical pond aquaculture literature warranted an approach which categorized information available for a restricted set of individual species (Table 1).

The synopsis also was restricted to considering only those environmental factors which typically do not degrade culture conditions to levels detrimental to the raising of quality food fishes for human consumption. Although chemicals are frequently used to reduce levels of competing or deleterious organisms in pond culture (Hickling 1962), we have not considered topics such as environmental contamination and toxicology. Studies dealing solely with intermediary metabolism were also excluded, and research on catabolic-anabolic processes was included only if there was a direct relation to growth, recruitment, or mortality.

A scheme for categorizing research on principles of spawning, egg development, and growth and mortality of juvenile and adult fish is presented in Tables 2 and 3. The classes are not mutually exclusive, nor are culture system dynamics defined by them in a non-interactive fashion, but in practice most research efforts could be categorized into one or several main areas.

RESULTS OF THE LITERATURE SEARCH

The literature examined for 1976-1980 was primarily confined to the aquaculture and fish biology journals published in English, French, and German

(which were catalogued in Cvancara 1976-1980) due to considerations of time, uniformity and extent of the search, and the language biases of the authors. The results of the search for the years 1976-1980 are presented in Tables 2 and 3.

Comparison of the totals for the cateories of pond culture principles in Tables 2 and 3 suggests that little change in the main directions of published research on dynamics of tropical fish culture occurred during the last half of the past decade. Even among the restricted set of species studied during 1976-1980, many areas appeared to have received quite minor effort. In some instances, research prior to 1976 may have been intense or concentrated in currently neglected areas. For example, the preceding decade saw much research on induced spawning of the mullet, Mugil cephalus (Kuo et al. 1973, 1974; Liao et al. 1971; Shehadeh and Ellis 1970; Shehadeh et al. 1973a, 1973b; Tang 1964; Yang and Kimm 1962; Yashouv 1969), which led to the successful practices currently used. Certainly, a large volume of research effort was neglected with the exclusion of government aquaculture and fishery publications, but there is little reason to believe that the directions and concentrations of research topics differed radically in this realm from that reported in the surveyed literature.

The little studied priniciples appear related to factors which influence fish growth indirectly

Table 1

LIST OF FISH SPECIES COMMONLY CULTIVATED IN TROPICAL PONDS

Finfish species considered in the reviewed literature for the years 1976-80. The list was compiled after consideration of Hickling (1962); Hora and Pillay (1962); Bardach and Ryther (1968); Bardach, Ryther, and McLarney (1972); Nelson (1976); and Brown (1977). The systematic status varies considerably for some taxa.

Family	Species
Anabantidae	Anabas testudineus
Anguillidae	Anguilla japonica
Belontiidae	Trichogaster pectoralis
	Trichogaster trichopterus
Chanidae	Chanos chanos
Channidae	Ophicephalus gachua
	Ophicephalus marulius
	Ophicephalus punctatus
	Ophicephalus striatus
Cichlidae	Etroplus suratensis
	Tilapia aurea
	Tilapia andersonni
	Tilapia galilaea
	Tilapia macrochir
	Tilapia melanopleura
	Tilapia mossambica
	Tilapia nigra
	Tilapia nilotica
	Tilapia rendalli
	Tilapia sparmanni
	Tilapia zillii
Clariidae	Clarius batrachus
	Clarius gariepinus
	Clarius macrocephala
	Clarius magur
Cyprinidae	Arstichthys nobilis
	Barbus carnaticus
	Barbus hexagonalis
	Carassius auratus
	Carassius carassius
	Catla catla
	Cirrhina cirrhosa
	Cirrhina molitorella
	Cirrhina mrigala
	Cirrhina reba
	Ctenopharyngodon idella
	Cyprinus carpio
	Hypophthalmichthys harmandi
	Hypophthalmichthys molitrix

Table 1 (continued)

Family	Species
Cyprinidae (cont.)	Labeo bata
	Labeo calbasu
	Labeo collaris
	Labeo fimbriatus
	Labeo kontius
	Labeo rohita
	Labeobarbus tambroides
	Megalobrama bramula
	Mylopharyngodon aethiops
	Mylopharyngodon piceus
	Osteochilus hasselti
	Osteochilus thomassi
	Parabramis pekinensis
	Puntius belinka
	Puntius gonionotus
	Puntius japonicus
	Puntius javanicus
	Puntius orphoides
	Puntius schwanefeldi
	Squaliobarbus curiculus
	Tinca tinca
	Thynnichthys sandkhol
Eleotridae	Oxyeleotris marmoratus
Elopidae	Elops saurus Bleeker
	Megalops cyprinoides
Helostomidae	Helostoma temmincki
Heteropneustidae	Heteropneustes fossilis
Latidae	Lates calcarifer
Mugilidae	Mugil cephalus
	Mugil corsula
	Mugil dussumieri
	Mugil tade
Osphronemidae	Osphronemus goramy
Pangasiidae	Pangasius larnuaudi
	Pangasius micronemus
	Pangasius sanitwongsei
	Pangasius sutchi
Salmonidae	Salmo gairdneri
	Salmo trutta
Some generic synonymies:	Mugil = Rhinomugil, Tilapia = Sarotherodon, Puntius = Barbus in some classifications of species in the above list.

Table 2

SUMMARY OF KEY INFORMATION CONTAINED IN ALL AQUACULTURE AND FISH BIOLOGY LITERATURE EXAMINED FOR THE YEARS 1976-78 FOR FISH SPECIES COMMONLY CULTIVATED IN TROPICAL PONDS[a]

	A. japonica	C. chanos	O. punctatus	O. striatus	E. suratensis	T. aurea	T. galilaea	T. rendalli	T. mossambica	T. nilotica	T. zillii	C. batrachus	C. macrocephala	C. auratus	C. catla	C. mrigala	C. idella	C. carpio	H. molitrix	L. bata	L. calbasu	L. rohita	T. tinca	H. fossilis	M. cephalus	T. trichopterus	S. gairdneri	S. trutta	Total
Natural maturation/ spawning				1	1				3					5			1	2		1				3		2	4		23
Fecundity relations																								1				1	
Fecundity management through stock																													0
Spawning habitat manipulation		1																											1
Spawning induction/ prevention									2	1	2	1	1	5	1	1	7	4	2					10			2		39
Embryonic/larvel development																													0
Antagonism- facilitation									1						1	1		1	1			1					3		9
Abiotic environmental limitation														1				2			1			2	1		7	1	15
Ingestion/feeding pattern				1		1	1				1				1		1							1	2		6		15
Locomotor activity				2										4				1						1					8
Evacuation time/egestion/excretion																									1		2	1	4
Empirical food conversion efficiency/ growth and nutrition	7		1	1		1	1	3	3	1	3	2		2	1	2	5	14				2	2	2	2		32	8	95

[a]Government publications and unpublished symposia, conferences, and dissertations were not included. Information pertaining to diet-related diseases and metabolic rate and scope are not included.

Table 3

SUMMARY OF KEY INFORMATION CONTAINED IN ALL AQUACULTURE AND FISH BIOLOGY LITERATURE EXAMINED FOR THE YEARS 1978-80 FOR FISH SPECIES COMMONLY CULTIVATED IN TROPICAL PONDS[a]

	A. japonica	C. chanos	O. punctatus	O. striatus	E. suratensis	T. aurea	T. galilaea	T. rendalli	T. mossambica	T. nilotica	T. zillii	C. batrachus	C. macrocephala	C. auratus	C. catla	C. mrigala	C. idella	C. carpio	H. molitrix	L. bata	L. calbasu	L. rohita	T. tinca	H. fossilis	M. cephalus	T. trichopterus	S. gairdneri	S. trutta	Total
Natural maturation/ spawning		1	3	2					1	1	3	2		3				2						2			5	1	26
Fecundity relations			1							1				1															3
Fecundity management through stock																													0
Spawning habitat manipulation																	1												1
Spawning induction/ prevention		2	1			3			1	2		1		5			3	4	1					2			9		34
Embryonic/larval development																													0
Antagonism- facilitation						1												1											2
Abiotic environmental limitation			1			1						2	2	1			2	7	1			1		1			12	4	35
Ingestion/feeding pattern										1							1							1	1		1	1	6
Locomotor activity														1										1				1	3
Evacuation time/egestion/excretion											2																3		5
Empirical food conversion efficiency/ growth and nutrition	1	1	1	1		1		1	1	2	2			4		2	3	18	1				1	3			27		71

[a]Government publications and unpublished symposia, conferences, and dissertations were not included. Information pertaining to diet-related diseases and metabolic rate and scope are not included.

(Weatherley 1976). Nevertheless, such mechanisms may be of paramount importance in production dynamics and in bioenergetics models developed for analysis and prediction of yield. Weatherley (1966, 1972) stressed the importance to fish population dynamics of such ecological processes. The relatively well-researched categories in Tables 2 and 3, other than spawning and spawning induction, were ingestion rates and feeding patterns in 1976-1978, and the categories of abiotic environmental limitation and food conversion efficiency and nutrition during both periods. Ethological factors, such as locomotor activity and antagonism-facilitation interactions, in general were poorly researched. Such factors can significantly alter directions of energy flow through populations. For example, the effect of increased locomotor activity on metabolic scope can drastically reduce energy available for growth (Webb 1978).

One major area of research virtually ignored in this synopsis was that of larval development of cultured tropical fishes. This is particularly problematic because the production of viable fish fry is of utmost importance to intensive aquacultural projects. However, the current techniques of fry-rearing are more realistically considered a management practice rather than a biological principle, and were not a major part of this synopsis.

ECOLOGICAL PERSPECTIVE

The ecological processes relating stock density, growth, and mortality may be approached through Fry's (1947, 1971) paradigm of limiting controlling, masking, lethal, and directive factors, or through the Hutchinsonian niche (Whittaker and Levin 1975) in which somatic and protein growth are fitness values which are maximized in pond culture. The Fry perspective is primarily concerned with physico-chemical impacts on species populations and is thus fundamentally autecological, whereas niche considerations ultimately are synecological, as both intra- and interspecific impacts are at the foundations. The synthesis of these two perspectives into a sound practical and theoretical basis for fisheries management awaits the formulation and resolution of theories and models on intra- and interspecific interactions, in metabolic terms (Werner 1980). Webb (1978) has provided an examination of the metabolic bases of ecological processes, although the relation of conspecific density or species interactions to mechanisms affecting growth was not stressed.

Although the empirical effects of population density on growth are generally established for fish (Beverton and Holt 1957; Backiel and LeCren 1967, 1978) an understanding of the various behavioral and physiological mechanisms controlling density-dependent responses has scarcely been realized.

Genetic selection of stocks for optimal growth under high stocking rates could be more effectively pursued if behavioral bases of metabolic costs were known. This genetic selection for rapid growth requires physiological and bioenergetic analyses of growth (Weatherley 1976). Assimilative capacity and growth potential must account for effects of population density in relation to frequency and size of food rations, due to conflicting factors of social facilitation and behavioral dominance (social inhibition) (Weatherley 1976). The energetics of activity need examination, because if caloric costs of stressed and routine activity are high, decrements to growth from net (physico-logically useful) energy may be significant (Noakes 1978). The proportion of net energy allocated to activity under stressed, routine, and basal metabolism differs substantially (Weatherley 1976; Webb 1978). Some metabolic features, such as specific dynamic action (SDA), which are indirectly related to stock density, may not be reduced through genetic selection. In such instances, densities in polycultured communities may be manipulated to optimize overall food utilization.

A bioenergetic approach for evaluating effects on growth and production arises from the balanced energy equation of Ivlev (1939) and Winberg (1956).

$$Q_G = pQr - Q_M \quad (1)$$

where:

Q_G = growth (anabolism)

p = proportion of food energy consumed which is assimilated,

Q_R = food consumed, and

Q_M = metabolism (catabolism).

These quantities are properly considered as rates in time. It should be noted that Q_G contains both somatic and gonadal components, and that Q_M may contain energy devoted to reproductive behavior. In its expanded form, the equation may be expressed (after Webb 1978):

$$Q_R - (Q_F + Q_N) = Q_S + Q_L + Q_{SDA} + Q_G \quad (2)$$

where:

Q_F = faecal loss,

Q_N = excretory or non-faecal loss,

Q_S = standard metabolism,

Q_L = locomotor (activity) metabolic cost, and

Q_{SDA} = apparent specific dynamic action.

Thus,

$$Q_M = Q_S + Q_L + Q_{SDA} \quad (3)$$

A further useful concept is that of metabolic scope, equal to:

$$Q_{m_{max}} - Q_S \quad (4)$$

An outline of the primary mechanisms of density effects on growth is presented in Table 4. Mechanisms leading to negative changes in Q_G in culture systems would be classified as intra- and interspecific competition (Pianka 1978), whereas various positive growth rate effects could be considered as protocooperation, commensalism, or mutualism. Protocooperation refers to both intra- and interspecific interactions resulting in positive growth, while mutualism (obligate reciprocol positive) and

Table 4

FISH POPULATION INTERACTIONS - MECHANISMS OF DENSITY EFFECTS ON GROWTH[a]

Primary mechanisms	Category of ecological interaction, losses (-), or gains (+) to growth rate (QG)	Principal rates affected and direction in balanced energy equation	Description	Examples
Immune hypersensitivity antigen-anitibody	Intraspecific competition - Interspecific competition -,-	$+Q_L$, $+Q_S$, $-Q_R$	Antigen anaphylactic responses	Henderson-Arzapalo et al., 1980; Smith 1977
Metabolite	Intraspecific competition - Intraspecific competition -,-	$+Q_L$, $+Q_S$, $-Q_R$	Sublethal NH_3, CO_2 effects	Burrows, 1964; Kawamoto, 1958, 1961; Kawamoto et al., 1957; Smith, 1972; Yashouv, 1958
Hormone	Intraspecific competition - Intraspecific protocooperation +	$\pm Q_S$, $\pm Q_L$, $\pm Q_R$	Conditioning crowding factors	Allee et al., 1940; Pfuderer et al., 1974; Timms, 1975; Yu and Perlmutter, 1970.
Activity	Intraspecific competition - Interspecific competition -,- Intraspecific protocooperation Intraspecific mutualism +	$\pm Q_L$	Schooling effects on hydrodynamics, non-chemical density effects on locomotion, agonistic and dominance interactions	Breder, 1965; Li and Brocksen, 1977; Marr, 1963; Parker, 1973; Schlaifer, 1938, 1939; Weihs, 1973; Yamagishi, 1962, 1964.
Social feeding facilitation/ antagonism	Intraspecific competition - Intraspecific mutualism + Intraspecific protocooperation + Interspecific competition -,- Interspecific protocooperation +,+	$\pm Q_R$, $\pm Q_{SDA}$, $\pm Q_N$, $\pm Q_F$	Schooling, density effects on diet, feeding rates	Ivlev, 1961, Nikol'skii, 1955; LeCren, 1965; Kawanabe, 1969; Brown, 1946.
Non-social feeding facilitation/ antagonism	Intraspecific competition - Intraspecific protocooperation + Interspecific protocooperation +,+ Interspecific commensalism +,0 Interspecific competition -,-	$\pm Q_R$, $\pm Q_{SDA}$, $\pm Q_N$, $\pm Q_F$	External environmental food processing effects on food conversion and trophic transfer efficiencies	Kilgen and Smitherman, 1971; Yashouv, 1966.
Food-habitat shifts	Intraspecific competition - Interspecific competition -,-	$-Q_R$, $+Q_{SDA}$, $+Q_N$, $+Q_F$	Habitat-niche expansion and packing, occupation of sub-optimal marginal habitats	Nilsson, 1963, 1967; Svardson, 1976; Werner and Hall, 1976, 1977.

[a]Category of ecological interaction after Pianka (1978). The balanced energy equation is the expanded version, Eq. (2), wherein Q_R = food energy consumed, Q_S = standard metabolism, Q_L = activity metabolism, Q_{SDA} = apparent specific dynamic action, A_N = excretory loss of non=faecal loss, Q_F = faecal loss.

commensalism (positive-neutral) impacts refer to interspecific interactions. Direct competitive interactions are classed as interference (production of toxins and agonistic or territorial behaviors), but less direct effects are exploitation (those arising through reduction of unheld resource levels). The competitive mechanisms of immune hypersensitivity, metabolite loading, and hormonal antagonisms are chemical interference interactions, while the negative density-dependent growth impacts from activity, food-habitat shifts, and social feeding antagonisms are primarily physical interferences.

Although acute immune hypersensitivity responses leading to disease and death are often observed (Smith 1977; Henderson-Arzapalo et al. 1980), chronic cutaneous anaphylactic reactions likely increase Q_L and Q_S, and decrease Q_R.

Metabolite growth interferences have been summarized by Webb (1978). He indicates that Q_S and Q_R are relatively insensitive to elevated levels of CO_2 and nitrogenous wastes. Thus, Q_L increases in metabolism, through general excitability rates, appear to be the dominant growth reducing effect of metabolites. Effects on Q_{SDA} involving costs per unit ration (through Michaelis-Menten kinetics) appear unevaluated. Hyperexcitability in fishes exposed to increased ammonia levels is well documented (Wuhrman and Woker 1948; Fromm and Gillett 1968; Olson and Fromm 1971). Growth reductions have been observed in rainbow trout and chinook salmon, respectively, following chronic dosings at levels from 0.005-0.015 mg/L un-ionized ammonia (Smith 1972; Burrows 1964).

Hormone effects, which like the former categories are observed as conditioning or crowding factors, may increase (Allee et al. 1940) or decrease (Pfuderer et al. 1974; Yu and Perlmutter 1970) growth rates, through Q_S, Q_L, and Q_R. The relative importance of these components, as well as the general importance of hormones to growth, remains largely speculative.

Activity (Q_L) effects on growth are produced through several density-controlled mechanisms. Increased efficiency of locomotion due to mucus reduction of drag (Breder 1976), and hydrodynamic considerations of vortex production (Weihs 1973; Breder 1965) are possibly advantageous aspects of schooling (Krebs 1976). Schooling positively contributes to Q_G in some species through declines in general excitability or "calming" effects (Parker 1973; Schlaifer 1938, 1939). Heightened general excitation levels may lead to increased metabolic rates in territorial species or in habitats where territoriality is enhanced (Yamagishi 1962; Li and Brocksen 1977). These general excitation effects due to increased density are similar to effects produced by metabolite build-up; probably both mechanisms often occur together with territorial species in intensively cultured pond systems with negligible water turnover. Spontaneous activities and increased responses to stimuli have an ultimate effect of increasing Q_M beyond Q_S. Elevation of routine metabolism may be a major diversion from growth as routine metabolic costs may reach one-third to one-half of metabolic scope (Webb 1978). Additionally, some species may exhibit high levels of agonistic activity as well as higher metabolic levels due to decreased locomotor efficiency in more rigorous microhabitats. Both demonstrably reduce Q_G (Magnuson 1962; Eaton and Farley 1974; Li and Brocksen 1977).

The definition of sociality used in Table 4 is an expansion of Noakes' (1978) definition as behavior directly related to actual or potential encounters between conspecifics to include interspecific interactions involving communication. Interspecific agonistic behaviors and dominance relationships associated with feeding may impact particularly strongly on ration when man introduces exotic species to communities (Nilsson 1967). Further influences of sociality on feeding broadly overlap with chemical communication effects of feeding enhancement included under hormonal mechanisms. Reduction in Q_G through decreased foraging activity ($-Q_R$) due to time spent in defense of territories (e.g., LeCren 1965) frequently will coincide with increases in level of antagonistic activity mentioned previously. Landless (1976) found that confined rainbow trout showed differences in operant behavior to obtain food associated with territorial-dominance reactions. Physical interference from dominants that decreased average Q_R where food was not abundant has also been shown for Salmo trutta (Brown 1946) and Oryzias latipes (Magnuson 1962).

Social interactions also can increase feeding rates and influence diet composition. The advantages of gregarious feeding, such as enhanced foraging efficiencies via increased probability of locating food (Keenleyside 1955), may be more important to predatory species, or in systems where habitat heterogeneity is high and food is patchily distributed. However, plankton-eating fish may feed more intensively when in schools than when dispersed (Nikol'skii 1955). Social structure changes observed by Kawanabe (1969) in ayu, Plecoglossus altivelis, enhanced exploitation of food resources under changing availability. Learning rate in operation of self-feeders in rainbow trout is increased by presences of conspecifics (Adron et al. 1973). Noakes (1978) commented that fish kept in groups feed more readily and adapt to dietary changes more rapidly than do isolated individuals.

Total fish production in pond systems can be increased dramatically through polyspecific culture (Jhingran 1976). This phenomenon has long been known, particularly in the cases of Chinese and Indian carps (Bardach et al. 1972). Species which operate on different trophic levels, or forage differently, can use single or diverse food resources more efficiently and thus provide higher levels of total pond fish production (Hickling 1962; Yashouv 1958, 1966). Behavioral and physiological description and modelling of the energetics of food processing are uncommon in the literature. Foraging efficiency (Q_R), as well as ingested food conversion efficiency (Q_{SDA}, Q_N, Q_F), are rates affected in the balanced energy equation.

Food and habitat shifts are most frequently observed with exotic species introductions by man (Nilsson 1967). Segregation of habitat is probably the most important means of niche separation in freshwater fishes (Werner et al. 1977). Such shifts due to density effects may operate through a variety of interference and exploitation mechanisms (Nilsson 1967). The proximate causes of interference are similar to those present in social feeding antagonisms. The main difference lies in the displacement of less dominant individuals to habitats

where sub-optimal conditions depress feeding rates ($-Q_R$) and alter diets (effects on Q_{SDA}, Q_N, Q_F). The presence of a competitor should not alter the food consumption spectrum within a habitat, but may influence the amount of time spent foraging in that habitat relative to other habitats (Werner and Hall 1977). Depression of Q_G, therefore, is considered independently of costs of ambient agonistic interactions in this mechanism. It may be noted that when ration effects associated with habitat shifts occur, qualitative diet changes (e.g., away from carnivory or large food item sizes) may actually decrease Q_{SDA} per unit ration (by reducing amount of protein in the diet), although total apparent SDA may be increased. Also, total pond species production may also be augmented through more efficient filling of available habitats, especially in polyculture. Analytic research on food-habitat shifts are rare, especially for communities cultured in tropical pond systems.

FUTURE RESEARCH NEEDS

Based on the literature search of selected publications and the evaluation of ecological principles presented in this review, recommendations for future research can be made. Considerations such as parameter requirements for specific models, or the dynamics of a particular culture system, certainly could alter these recommendations. However, the greatest area of potential innovation in the biological principles regulating tropical pond culture systems is in the understanding of genetic enhancement of fitness and of density effects on fish quality and production. The following areas are of particular interest.

Few of the commonly cultured tropical species have been evaluated for genetic selection of superior growth, disease resistance, or hardiness (Amend 1976; Shepherd 1978), although this research has been of great value to other culture systems (Donaldson and Olson 1957; Moav et al. 1976; Moav and Wohlfarth 1976; Gjedrem 1976).

Interactions between genetics, habitat structure, and bioenergetics in culture situations have seldom been examined (Bams and Simpson 1976), and may be very important in optimizing growth and yield of cultured fish.

Parasite and disease effects on growth rate have been little studied (Webb 1978), and the relationship between density (or competition) and parasite-disease effects on growth is unknown.

Polyculture community dynamics are not well understood, in spite of the prevalence of polyculture systems.

Density effects on food processing efficiency, occurring as a result of social interactions, metabolite levels, and locomotor effects, have received little attention for most species listed in Table 1.

The effects of habitat structure on optimal stocking density are virtually unknown in field situations (Bams and Simpson 1976; Leon 1975).

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APPENDIX A

SELECTED ADDITIONAL BIBLIOGRAPHY: GENETIC AND COMPETITION FACTORS GOVERNING GROWTH

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A STATE OF THE ART OVERVIEW OF AQUATIC FERTILITY WITH SPECIAL REFERENCE TO CONTROL EXERTED BY CHEMICAL AND PHYSICAL FACTORS

by

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and

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INTRODUCTION

Efforts to produce high quality animal protein for human consumption through aquaculture have often been directed towards intensive fish production using formulated feeds. Although many fish can efficiently convert artificial feeds to flesh, fish generally require two to four times greater dietary protein than warm-blooded domesticated animals [1]. Fish diets rely heavily on high quality protein meals which often are suitable for direct addition to the human diet. The conversion of edible protein sources to fish flesh in lesser developed countries is suspect if the goal is to increase available dietary protein for humans.

Channel catfish can be used as an example of an intensively cultured fish to demonstrate the efficiency of feed protein converted to edible fish protein. Catfish are harvested for human consumption after 18-22 months of production at an average weight of about 1.25 lbs. At a food conversion rate of 1.5:1, each fish has been fed about 1.875 lbs. of feed. Since commercial catfish feeds contain about 36% protein, each fish has consumed about 0.675 lbs. of protein. Only about 0.5625 lbs. of edible fish flesh is available from each fish produced (1.25 lbs. x 45% dressout to filets) which contain about 0.107 lbs. of protein (0.5625 lbs. x 19% protein wet weight). Consequently, the percent of protein fed which is recovered is about 15.85% [(0.107 lbs. protein in flesh/0.675 lbs. protein fed) x 100].

Broiler chickens are as efficient as channel catfish in converting dietary protein to edible flesh protein. A broiler is ready for market after 7-8 weeks at a weight of approximately 4.12 lbs. Each chicken has been fed about 8.07 lbs. of feed containing 1.74 lbs. of protein (2.54 lbs. of starter at 23% protein and 5.53 lbs. of finisher at 21% protein or 0.58 and 1.16 pound of protein, respectively) with a feed conversion of 1.96:1. The finished broiler provides about 0.29 lbs. of protein available for consumption (4.12 lbs. live weight x 66% dressout x 60% edible meat x 18% protein wet weight). Consequently, the percent protein fed which is recovered is about 16.67% [(0.29 lbs protein in flesh/1.74 lbs. protein fed) x 100].

Despite similar protein conversion ratios, chickens would appear to be more desirable converters to high grade protein because of their 7-8 week turnaround-time as opposed to the 18-22 months required for catfish. However, production of both chickens and catfish in a feedlot manner results in significant loss of edible protein.

Production of certain fishes in lesser developed countries has been limited by the availability of appropriate feed items in culture ponds throughout the rearing period. Supplemental feeding has often been suggested to augment pond fertilization practices. As an example, the production of Chanos chanos in developing countries has been limited by available periphyton in culture ponds near the end of production [2]. The protein requirements for maximum growth of C. chanos fry has been established at 40% of the diet [3]. If protein requirements of adults are similar to fry and C. chanos is as efficient as channel catfish in converting protein fed to edible protein, the net result still would be a loss in edible protein during final production feeding.

The character of the nutrients in the animal wastes, particularly nitrogen resulting from degraded protein, again favors chickens. Chicken wastes are a concentrated nutrient-rich fertilizer which can be stored and applied when and where needed to enhance either terrestrial or aquatic fertility. The wastes from the fish release nutrients in a continuous and diffuse manner to the aquatic system yielding little opportunity to control aquatic productivity by adjusting nutrient availability.

The loss of edible protein with either fish or chickens fed protein-rich foodstuffs can lead to reductions in the protein level of the human diet in lesser developed countries in that the increased market cost of the higher grade protein is often beyond the means of a significant portion of the population. If the decision is made to upgrade protein on a large feedlot scale, the advantage would appear to lie with chickens in that the turn-around time is shorter and the waste nutrients are in a concentrated form allowing better potential for enhancing primary

productivity. Overall, it appears that feedlot aquaculture should be avoided in lesser developed countries.

BASIN CHARACTERISTICS

As was shown in the preceding discussion, the probability of significantly increasing protein yield to the people of third world countries from aquaculture systems directly dependent on external food sources for the fish is, at best, extremely limited. The primary objective of aquaculture in such countries is to increase production of protein in the human diet, but the challenge is to maximize protein yield from the base supplied by aquatic photosynthesis without relying on protein and energy-rich external foodstuffs.

Any manipulation of third world aquatic ecosystems to increase protein production must be accomplished, in most cases, without benefit of the energy and resource demanding technologies common to more industrialized societies. In such impoverished areas, enhancement of protein yield must be accomplished by simple manipulations aimed at approaching the maximum potential yield within the limits prescribed by the physical, chemical, and biological interactions peculiar to each system.

Ponds, like soups, differ greatly in nutritive content and the fertility of each pond, to a large extent, is dependent on where the water has been before it entered the pond. The remarkable solvent properties of water allow it to transport a multitude of both natural and man-added inorganic and organic materials in the dissolved state. The erosive character of water also allows the transport of a great variety of particulate materials. The combination of dissolved and particulate materials present in a water interact with physical parameters such as temperature and light to dictate limits to both type and amount of aquatic photosynthesis. As such, the fertility of freshwater ponds reflect the drainage basin in which they lie. Thus, local geology and climate, together with terrestrial vegetation and type and amount of human use and perturbation of the land in the drainage basin to each pond, dictates the base physical and chemical character of the water in that particular pond. The interplay between the myriad variables involved guarantees variation in fertility from pond to pond and from region to region.

The various physical, chemical, and biochemical weathering reactions responsible for formation of soils from the parent rock yield significant cation release. With the abundance of water in humid climates, those released cations are washed from the soil leaving less fertile soils dominated by iron and aluminum silicates and oxy-hydroxides. The end result of a long history of such weathering in a humid climate is a basin which yields runoff water with low concentrations of dissolved minerals.

In more arid climates, the decreased water throughput associated with decreased precipitation and increased evaporation is not sufficient to wash out the cations released by weathering. The result is a basin dominated by more complex cation-rich clays from which the runoff water contains elevated concentrations of dissolved minerals.

In general, water from well-weathered drainage basins in humid climates or from areas of igneous rock with low solubility will contain reduced carbonate-bicarbonate alkalinity and total hardness. Waters from calcareous or historically more arid drainages will contain much higher alkalinity and hardness. An example of this is seen in data presented by Kempe [4] which indicates an alkalinity averaging about 2.2 meq/ℓ in the Elbe River compared with an alkalinity of only about 0.4 meq/ℓ in the Amazon River.

ALKALINITY

In freshwater ponds and lakes, the bicarbonate-carbonate alkalinity plays a key role in dictating the potential productivity such systems can exhibit. The carbonate-bicarbonate alkalinity system serves simultaneously as the only significant buffer controlling the pH of the water and the only significant reserve source of carbon dioxide available for support of aquatic photosynthesis.

Carbon dioxide gas dissolves in water to form carbonic acid. Increased acidity associated with carbon dioxide gain by rainwater as it perculates through the organic-rich surface layers of terrestrial soils accelerates weathering of parent materials yielding increased bicarbonate alkalinity in the water.

The two dissociations of carbonic acid shown in Equations 1 and 2 play a primary role in pH buffering in freshwater systems.

$$CO_2 + HOH \rightleftarrows HCO_3^- + H^+ \quad (1)$$

$$H^+ + CO_3^= \rightleftarrows HCO_3^- \quad (2)$$

Combination of the first and second dissociations of carbonic acid to yield Equation 3 indicates the total reaction of this primary buffer system.

$$2HCO_3^- \rightleftarrows CO_2 + CO_3^= + HOH \quad (3)$$

The first and second dissociations of carbonic acid are both characterized by dissociation constants as shown in Equations 4 and 5.

$$K_1 = \frac{[HCO_3^-][H^+]}{[CO_2]} \quad (4)$$

$$K_2 = \frac{[CO_3^=][H^+]}{[HCO_3^-]} \quad (5)$$

Solving each of these equations for HCO_3^- yields the equality shown in Equation 6.

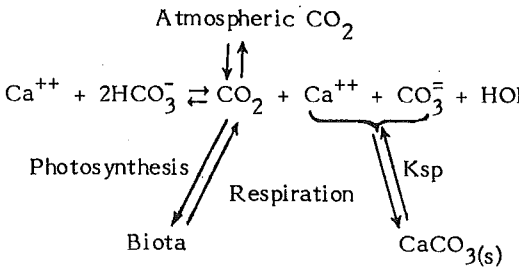
$$[HCO_3^-] = \frac{K_1[CO_2]}{[H^+]} = \frac{[CO_3^=][H^+]}{K_2} \quad (6)$$

Rearrangement of Equation 6 yields Equation 7, which, in an oversimplified fashion, indicates the inter-

dependency of pH, the available carbon dioxide level and the alkalinity system in freshwater.

$$[H^+] = \sqrt{K_1 K_2 \frac{[CO_2]}{[CO_3^=]}} \quad (7)$$

The first and second dissociations of carbonic acid together with the solubility of carbonate salts, atmospheric carbon dioxide and extraction and return of carbon dioxide by aquatic photosynthesis and respiration shown in Equation 8 determine the pH of freshwaters.



In the absence of nitrogen, phosphorus, and other nutrients required for aquatic photosynthesis, the pH of the water would be controlled by atmospheric carbon dioxide and the alkalinity of the water. Representative equilibrium pH values are presented in Figure 1 for an atmospheric carbon dioxide concentration of 340 ppm, a temperature of 20 C, and alkalinities of 5 to 300 mg $CaCO_3/\ell$. The total inorganic carbon present in the water under these conditions also is presented in Figure 1.

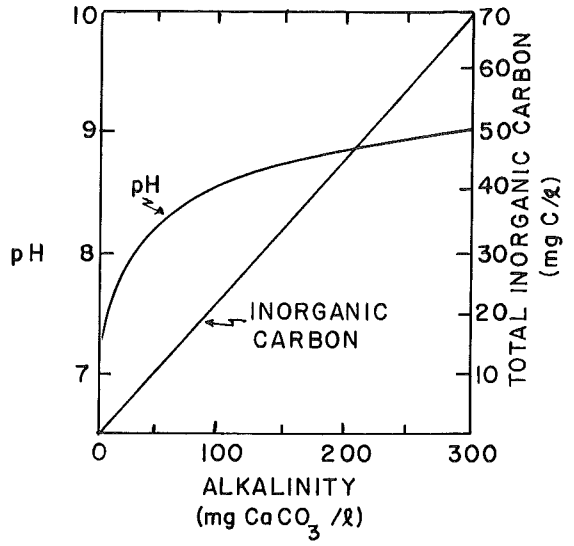


Figure 1

Total inorganic carbon content and pH of freshwater at various carbonate-bicarbonate alkalinities at equilibrium with an atmospheric carbon dioxide level 340 ppm at 20 C.

Addition of nutrients which allow photosynthetic uptake of carbon dioxide by aquatic plants at a rate faster than it can be supplied by the atmosphere or respiratory sources leads to an increased pH and a concomitant reduction in the carbon dioxide concentration of the water as shown in Figure 2.

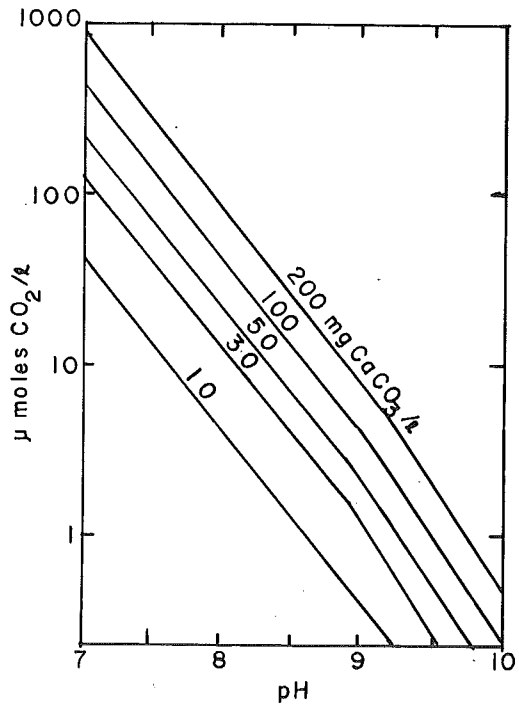


Figure 2

Carbon dioxide content of freshwater as a function of pH and carbonate-bicarbonate alkalinity of the water.

In order for atmospheric carbon dioxide to enter water, the carbon dioxide concentration of the water must be reduced to a level less than that at atmospheric equilibrium (13.2 μmoles CO_2/ℓ for an atmospheric content of 340 ppm and a water temperature of 20 C). In a pond, this reduction is accomplished by the photosynthetic fixation of carbon dioxide by aquatic plants at a rate greater than the rate of supply by respiration. However, the carbonate-bicarbonate alkalinity of a water determines the amount of carbon dioxide which must be fixed before atmospheric recarbonation becomes a significant source of photosynthetic carbon.

The amount of photosynthetic carbon fixation necessary to reduce the free carbon dioxide concentration of the water (CO_{2_f}) from 13.2 μmoles/ℓ to 1.32 μmoles/ℓ (100 percent to 10 percent saturation at 20 C with an atmospheric content of 340 ppm carbon dioxide) is shown for a wide range of alkalinities in Figure 3. Clearly, a much greater amount of photosynthesis must occur at high alkalinities before atmospheric recarbonation reaches the rate found at

low alkalinities after only a small amount of photosynthetic carbon fixation.

The amount of phosphorus required for algae to accomplish the amount of carbon fixation indicated in Figure 3, assuming a carbon to phosphorus atomic ratio of the algae of 100:1, also is given in Figure 3. If no phosphorus is available, there will be no algal photosynthesis and consequently, no diffusion of atmospheric carbon dioxide into the water. As indicated in Figure 3, the amount of phosphorus necessary to allow reduction of the CO_{2_f} concentration from 13.2 to 1.32 μmoles CO_2/ℓ is dependent upon the alkalinity of the water. It should be noted that at an alkalinity of 5 mg $CaCO_3/\ell$, the required amount of phosphorus is only 4.3 μg P/ℓ, while at an alkalinity of 300 mg $CaCO_3/\ell$, the required amount of phosphorus is 291.7 μg P/ℓ. Thus, the amount of phosphorus a pond can tolerate before exhibiting reduced carbon dioxide concentrations is a function of the alkalinity of the pond water which, in turn, is a function of the drainage basin in which the pond lies. Likewise, the amount of algal production allowed prior to establishment of low levels of carbon dioxide in the water also is a function of the alkalinity, increasing with increased alkalinity. As the carbon dioxide concentration of a water is reduced, the specific net carbon fixation rate for algae [5,6] and aquatic plants [7,8] is reduced. In general, the specific net carbon fixation rate of algae and submerged aquatic plants can be fit to the Michaelis-Menton model if corrections are made for the threshold carbon dioxide concentration required to initiate net photosynthesis as indicated in Equation 9.

$$\mu = \mu max \frac{C-C_q}{(K_c-C_q) + (C-C_q)} \quad (9)$$

where: μ = specific net carbon fixation rate ($Time^{-1}$)

μmax = maximum specific net carbon fixation rate ($Time^{-1}$)

C = existing carbon dioxide concentration (μmoles CO_2/ℓ)

K_c = carbon dioxide concentration at which $\mu = 0.5\ \mu max$ (μmoles CO_2/ℓ)

C_q = threshold carbon dioxide concentration required to initiate net carbon fixation (μmoles CO_2/ℓ)

At least for the alga Chlorella vulgaris the terms μmax, K_c and C_q are all functions of available light intensity [6] indicating marked interaction between the existing concentration of carbon dioxide and light intensity as shown in Equation 10.

$$\mu = f_1 light \frac{C - f_2\ light}{(f_3\ light - f_2\ light) + (C - f_2\ light)} \quad (10)$$

The threshold carbon dioxide concentration required to initiate net photosynthetic carbon fixation varies by orders of magnitude between different algae at any given light intensity [6]. The bluegreen alga

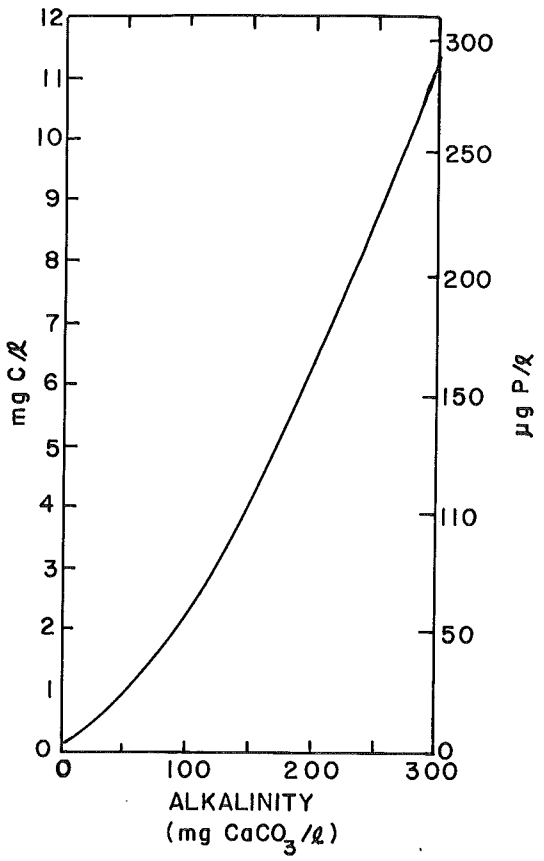


Figure 3

Amount of inorganic carbon which must be removed from various carbonate-bicarbonate alkalinities to reduce carbon dioxide from 100 to 10 percent saturation with an atmospheric carbon dioxide level of 340 ppm at 20 C given with the amount of phosphorus required for algal fixation of that carbon.

Anacystus nidulans exhibits the lowest Cq of all algae evaluated to date [6]. In nutrient enriched water, photosynthetic uptake of carbon dioxide by aquatic plants often exceeds the rate of recarbonation by atmospheric and respiratory carbon dioxide yielding decreasing carbon dioxide concentrations with time. This results in a decreased net specific carbon fixation rate by the plants but also in an increase in the net specific sinking rate of green algae [6]. The result of this accelerated sinking is the loss of the green algae at carbon dioxide concentrations in two of the three orders of magnitude higher than the threshold concentrations to which they are physiologically capable.

Bluegreen algae tend to become more buoyant with photosynthetic stress induced increase in vacuole formation [9,10]. King [11,12] suggested that the probability of bluegreen algal dominance increased with decreased carbon dioxide concentration of the water and both King [11,12] and Shapiro [13] suggested that bluegreen algae are better able to function at low carbon dioxide levels than are green algae. King [12] used this consideration to suggest

that the amount of phosphorus required to initiate bluegreen algal dominance in a lake increases with the additional carbon dioxide available with increased alkalinity of the water.

From available data, it appears that decreasing carbon dioxide concentrations in productive waters resulting from uptake of carbon dioxide by aquatic plants at rates exceeding recarbonation from atmospheric and respiratory sources play an important role in dictating the type of plant the water will support. The maintenance of carbon dioxide concentrations sufficient to minimize dominance by bluegreen algae appears to be determined by light availability, phosphorus, nitrogen, and alkalinity content of the water and detention time of the water in the pond [14].

The amount of carbon dioxide available for support of desirable plants prior to development of dominance by bluegreen algae also is a function of the alkalinity. The addition of only small amounts of phosphorus is required to fix the small amount of carbon necessary to reduce the carbon dioxide to the level favoring bluegreen algae in extremely soft waters. In hard waters with high alkalinities, sufficiently more nutrient can be tolerated and much more desirable algae will be produced prior to establishment of the bluegreen algae. Thus, it appears that the amount of aquatic photosynthate of a type of widespread value to aquacultural production as a function of nutrient addition is, in turn, a function of the alkalinity of the pond water which is determined by the drainage basin to the pond.

This relationship of pond productivity to the alkalinity of the water is not a recent observation. After their investigation of a great variety of lakes, Birge and Juday [15] suggested in 1911 that free carbon dioxide and available bicarbonate were the factors most likely limiting algal production in natural waters. Moyle [16] related both type and abundance of aquatic plants to the alkalinity of the water and Ball [17], Turner [18], and Hayes and Anthony [19] found increased fish production with increased alkalinity. King [11,12] discussed the role of alkalinity in the determination of both qualitative and quantitative changes in algal activity. Wright [20], Wright and Mills [21], Bartsch and Allum [22], Welch [23], and many other investigators have suggested that algal production was limited by the availability of a photosynthetic carbon source associated with the alkalinity in a wide variety of waters.

Moyle [24] suggested that natural waters with increased alkalinity also would tend to contain increased concentrations of other ions required for photosynthesis. Schindler et al., [25] present evidence that appreciable amounts of carbon dioxide can be gained from the atmosphere and that aquatic plant photosynthesis would not be totally limited by an absence of carbon dioxide. However, decreased carbon dioxide levels do result in both decreased specific net carbon fixation rates [6] and increased probability of bluegreen algal dominance [11,12,13].

In aquacultural ponds, the nutrient content is elevated by adding both organic and inorganic fertilizers. In such systems, increased reliance is placed on atmospheric carbon dioxide and the result often is the development of dominance by bluegreen algae, particularly if the alkalinity of the water is low. Under such conditions, the atmosphere continues to provide carbon dioxide but the resulting photosynthate is represented largely by bluegreen algae.

One of the major vexations in the management of water quality of lakes, ponds, reservoirs, wastewater treatment ponds, and particularly of aquacultural systems is the establishment of bluegreen algal dominance of the phytoplankton. In contrast to green algae and diatoms, which are valuable initiators of the aquatic food chain, the bluegreen algae are not readily used by the more desirable members of most aquatic systems. Rather, they often serve primarily as an energy source for bacteria and when used by the bacteria, often yield a deleterious impact on the dissolved oxygen resources of the water body. In addition, the gas vacuoles of the bluegreen algae increase their buoyancy causing them the accumulate near the water surface; thereby markedly decreasing light penetration and thus total photosynthetic activity of the pond.

NUTRIENTS

The biogeochemical cycle of phosphorus indicates the conservative nature of this element in the biosphere. Phosphorus has no permanent atmospheric sink but rather tends to be associated with both metal precipitates and exchange sites in both terrestrial and aquatic situations. The natural availability of phosphorus in freshwaters is determined by the same sorts of geologic and climatic factors which determine the general dissolved mineral content. But, the propensity of phosphorus to bind, in one way or another, with organic and inorganic particulates allows conservation of this nutrient within freshwater aquatic systems. Cycle and recycle of phosphorus through aquatic ecosystems, and particularly through shallow freshwater systems supporting rooted aquatic plants, allows maximum use of the phosphorus available in the production of aquatic photosynthate.

The conservative nature of phosphorus together with the extreme small concentrations required for production of freshwater aquatic plant biomass cause prime focus to be placed on phosphorus in the control of cultural eutrophication. These peculiarities of phosphorus, which are of detriment to the control of cultural eutrophication, are of real value in aquaculture in that only small concentrations of this scarce and often expensive nutrient are required to maintain optimal aquatic plant productivity.

As we noted earlier, the amount of phosphorus which can be added to a freshwater prior to establishment of dominance by bluegreen algae is a function of the alkalinity of the water. The role of alkalinity in maintaining pH of the water also is of import in that the solubility of many metal phosphates is related to the water pH.

Once added to a pond system, phosphorus tends to be conserved while other nutrients required to sustain pond productivity can be lost. Nitrogen is of particular import in this regard in that it is of obvious importance to protein formation and can be lost to the atmosphere both as ammonia, particularly with elevated water pH, and as nitrogen gas following denitrification.

The most probable nutrient sources available for aquaculture in third world countries are animal wastes. Morrison [26] gives data which yield nitrogen to phosphorus weight ratios for the wastes from various animals ranging from 6.42 for sheep for 2.11 for poultry. For optimal growth, aquatic plants require nitrogen to phosphorus ratios in the neighborhood of 7 to 8, indicating that animal wastes contain enough phosphorus for more aquatic photosynthesis than would be allowed by the nitrogen they contain. Clearly, any reduction in nitrogen availability will result in decreased protein content of the plants.

The addition of animal wastes to a pond stimulates both algae and macrophytes and yields increased productivity. Most commonly, such increased photosynthetic activity results in withdrawl of carbon dioxide from the water at rates faster than it can be replaced from respiration or atmospheric recarbonation yielding increased pH, with the rate of change being a function of pond alkalinity.

Nutrient induced increases in aquatic productivity lead to faster rates of biogeochemical nutrient cycle and increase the frequency with which each nitrogen atom will appear as ammonia. The increased rate of nitrogen recycle and the generally elevated pH in ponds where productivity is enhanced by nutrient addition leads to accelerated loss of nitrogen to the air as ammonia gas. Increased photosynthetic productivity also leads to increased probability of establishment of sufficiently reducing conditions at the pond bottom to promote nitrogen loss through denitrification.

The longer the detention time of the water in the pond, the greater is the probability that nitrogen will be lost to the atmosphere. Such loss can lead to significant reduction in the inorganic nitrogen available for plant photosynthesis. In a series of ponds charged with a good quality domestic wastewater, the nitrogen content of the water decreased as an exponential function of detention time as shown in Equation 11 [27].

$$N_t = N_o \, e^{-0.03t} \qquad (11)$$

where: N_t = total nitrogen concentration (mgN/ℓ) at time t.

N_o = initial total nitrogen concentration (mg N/ℓ).

t = detention time in days.

This loss of nitrogen leads to establishment of dominance by nitrogen fixing bluegreen algae in massive bloom proportions [28]. Bacterial use of these nitrogen fixing bluegreen algae leads to sufficient dissolved oxygen depletion to cause both summer and winter fish kills [28].

A major difficulty in maximizing yield and utilization of nutrients is in maintaining sufficient nitrogen and carbon dioxide concentrations to allow total expression of the phosphorus available in a form of aquatic photosynthate of value to the crop of interest being harvested from the pond. A linear series of ponds allows maximum use of the phosphorus added but nitrogen loss and carbon dioxide uptake from the alkalinity place carbon and nitrogen limits on the aquatic plants. In both cases, this yields bluegreen algal dominance in downstream ponds, with the detention time required being a function of the alkalinity, light, and phosphorus content of the water which interact to control both rate and extent of algal growth [29]. The absence of sufficient available nitrogen and the presence of other required growth factors yield nitrogen fixation and protein formation by heterocyst forming bluegreen algae. The ultimate challenge is to channel the protein supplied by such nitrogen fixation into products of value in the human diet. In this regard, some tropical fish may offer an opportunity of converting proteins from nitrogen fixing bluegreen algae to products of value in the human diet.

Although the cell walls of most plants are indigestible by alimentary canal secretions [30], bluegreen algae can be digested by fish since their cell walls differ in composition from higher plants [31]. The widely held view that bluegreen algae are trophicly unimportant does not appear to apply to some tropical fish [32]. Chanos chanos, Etrophs suratensis, Haplochromis nigripinnis, Mugil cephalus, and Tilapia nilotica are among the herbivorous fishes which consume forms of bluegreen algae (Table 1). These fishes digest bluegreen algae in the intestine after the cell walls have been lysed by stomach acid [33] or enzymatic hydrolysis [34,35,36]. Mugil spp. also have a gizzard which may increase the efficiency of enzymatic lysis of the bluegreen algal cell wall [35,36].

The ability to digest bluegreen algae does not indicate that total nutrient requirements can be met by these foodstuffs alone. Fishes which consume bluegreen algae often consume bacteria and protozoans associated with the algae (Table 1) which may assist in meeting their nutritional requirements [37]. Juvenile Tilapia nilotica and Haplochromis nigripinnis can assimilate up to 70-80% of the ingested carbon from Anabaena sp. and Microcystis sp. [38]. Due to diurnal patterns of stomach acid production [33], daily feeding cycles [39] and assimilation patterns [38] increase from shortly before dawn to dusk. T. nilotica and H. nigripinnis assimilate an average of about 43% and 66% of the total ingested bluegreen algal carbon per day, respectively. Apparently, juveniles and adults of these species can readily utilize bluegreen algae to meet most of their nutritional needs [38].

Because of the similarity between the cell wall composition of bluegreen algae and bacteria [31], enzymatic or acid lyses of bluegreen algae by species capable of using bacteria should be possible [36]. Other African cichlids including Tilapia esculenta [40], T. lencosticta [33], Sarotherodon mossambica [41,42], and Haplochromis spp. [33] have the ability to retain bluegreen algae in the stomach until pH values reach 1.6 or lower and should be able to digest bacteria and bluegreen algae. This hypothesis should be thoroughly tested to determine the growth potential of bactivorous and certain herbivorous fishes restricted to a diet composed chiefly of bluegreen algae.

Animal Interaction and Feedback

The type of fish a pond contains can exert significant control on both the type of plants the pond

Table 1

FISH CULTURED OR PROPOSED FOR CULTURE WHICH CONSUME FORMS OF BLUE-GREEN ALGAE

Species	Habitat[a]	Food habits
Chanos chanos - milkfish	M	benthic diatoms and multicellular plants, foraminiferans, mulluscs, dead copepods
	B	fry and fingerlings: Bacillariophyceae, Myxophyceae, degraded Chlorophyceae
		adults: diatoms, algae, fish eggs, etc.
	F - B ponds	fry and fingerlings: periphyton
		juveniles (50-100 mm): blue-green algae, diatoms, protozoans, and microcrustaceans mixed with detritus and minerals
		adults: benthic organisms and, reluctantly, filamentous algae
Etroplus suratensis - pearlspot	B - F	omnivorous: mainly blue-green and green algae, detritus, occasionally zooplankton, insects, worms, macrophytes, filamentous algae
Haplochromis nigripinnis	F	bacteria, blue-green algae, zooplankton
Mugil cephalus - grey mullet	F - M	plankton (blue-green, greens and occasional zooplankton), diatoms, aquatic plant soft parts, detritus
Tilapia nilotica - Nile perch	B - F	omnivorous: blue-green algae, detritus, higher plants

[a] M = marine, B = brackish, and F = freshwater environments.

supports and the nutrient cycling within the pond. If sufficient zooplankton are present in the pond to control the mass of green algae and diatoms, carbon extraction from the alkalinity may not proceed to the point where bluegreen algae dominate, thereby allowing sufficient light to reach the pond bottom to promote macrophyte growth. The addition of zooplanktivorous fish to such systems can reduce the zooplankton control of the algae to the point where large blooms of algae occur [43,44,45]. Such increases in algal mass are often sufficient to force a carbon dioxide level low enough for bluegreen algal dominance [11]. Development of blooms of algae can reduce light penetration sufficiently to cause the loss of macrophytes from a pond [46]. In fact, a pond totally dominated by macrophytes can be altered to total dominance by phytoplankton simply by adding zooplanktivorous fish [46]. However, macrophyte and periphyton dominance can be maintained by a sufficient population of pisciverous fish to keep the zooplanktivorous fish in check [46].

The significantly faster growth rates and shorter turnover time of algae suggest that their dominance over macrophytes would lead to much faster nutrient cycling in the pond. Such accelerated activity would increase the dynamic character of the pond and lead to increased fluctuation of most all parameters including dissolved oxygen concentration, light penetration, and pH and nutrient content of the pond water.

The addition of bottom feeding fish can accelerate the recycling of phosphorus in ponds [47] but, depending on the type of benthic sediments, may also increase turbidity of the water to the point where plant photosynthesis is light limited.

Obviously, the addition of toxic materials by human use of the water before or after it enters the pond will exert an effect on the system directly dependent on which organisms are affected. For example, Shapiro [48] cites the work of several investigators [49,50,51] which indicate development of heavy algal blooms associated with elimination of zooplankton by the addition of a variety of toxic materials.

OTHER BUFFERS

While in most freshwaters the carbonate-bicarbonate alkalinity serves simultaneously as the only significant pH buffer and reserve carbon source for aquatic photosynthesis, algal activity in nutrient enriched waters can stress this buffer allowing pH values of 11 or higher [11]. In addition to the importance of the alkalinity in controlling both pH and potential productivity, other buffers exercise control in some freshwater systems. Chief among these are organic and mineral acids which not only exert an influence of their own but also interact with the carbonate-bicarbonate system to exercise control of the biotic activity of such waters.

The carboxyl-laden organic acids common to many water [52,53] produced from both terrestrial

and aquatic vegetation [54] represent a significant ion exchange mechanism which interacts to destroy carbonate-bicarbonate alkalinity [55] in the manner shown in Equation 12.

$$R\text{-}COOH + M^+ + HCO_3^- \rightleftarrows R\text{-}COO(M^+) + CO_2 + HOH \quad (12)$$

In those basins where the accrual of such organic acids from both terrestrial and aquatic production exceed the accrual rate of cations from the weathering of the rocks and soil of the basin, carbonate-bicarbonate alkalinity will be destroyed and pH will be controlled by the organic acids. Since the pK's of these acids lie between about 4 and 5, the pH of the water will be below the level tolerated by methane forming bacteria and any accumulated organic matter will tend to be preserved in a manner leading to formation of peat. While they may not reach this bog state, highly colored waters in basins which supply few cations are not particularly productive. The low pH is buffered by the organic acids which tend to chelate metals and metal-phosphate complexes while the very low carbonate-bicarbonate alkalinity offers little reserve carbon dioxide for aquatic photosynthesis in these often light limited waters.

Mineral acids associated with the oxidation of iron pyrite exposed by strip mining or contained in "cat's clay" of marine origin or areas with exposed sulfide-rich shales pose a severe problem to aquaculture. Oxidation of exposed sulfides leads to acid formation in the manner shown in Equation 13 [56].

$$FeS_{2(s)} + 3.75\ O_2 + 3.5\ HOH \rightleftarrows Fe(OH)_{3(s)} + 2\ SO_4^= + 4\ H^+ \quad (13)$$

However, the resulting sulfuric acid reacts with various soil minerals in the manner shown for the overall reaction for Kaolinite in Equation 14 [57].

$$3\ FeS_{2(s)} + 2\ Al_2SiO_5\ (OH)_{4(s)} + 11.25\ O_2 + 10.5\ HOH \rightarrow Fe(OH)_{3(s)} + 6\ SO_4^= + 4\ Al^{+++} + 4\ H_4SiO_4^{\ o} + 2\ HOH \quad (14)$$

This process yields some pH rise over that for sulfuric acid but there is little change in titratable acidity since both 2 Al^{+++} and 6 H^+ require six equivalents of base for neutralization. Waters in basins which allow these reactions have a very low pH, are often extremely acid and are buffered by high concentrations of aluminum and/or iron.

Such waters can be recovered to an alkaline condition by adding organic material to a sufficient depth to allow establishment of sufficiently reducing microzones to favor bacterial sulfate reduction [57]. Under the low pH conditions, the resulting sulfide is lost to the air. This loss of hydrogen sulfide represents a biologically mediated titration of the acidity and, as pH increases, aluminum is precipitated as a hydroxide. Once the aluminum is precipitated, continued hydrogen sulfide loss results in increased formation of bicarbonate as shown in Equations 15 and 16.

$$CO_2 + HOH \rightleftarrows HCO_3^- + H^+ \quad (15)$$

$$H_2S_{(g)} \rightleftarrows HS^- + H^+ \quad (16)$$

Since the pK_1 for Equation 15 is 6.4 and the pK_1 for Equation 16 is 7.0, continued formation and release of hydrogen sulfide after the aluminum is precipitated is accompanied by continued bicarbonate increase. The result is a biologically mediated recovery of an extremely acid water to one which has a positive carbonate-bicarbonate alkalinity [57].

The problem with such a solution to mineral acids in aquacultural ponds lies in the need to promote anaerobic conditions at the pond bottom to generate the sulfides from sulfates required for recovery while maintaining an anaerobic seal to prevent further oxidation of pyrites in the benthic clays. Continued acid addition to the pond from the basin also would be a problem. However, organic materials are usually much more abundant than limestone in the areas in which such ponds are located and thus biological recovery may offer more potential than direct chemical neutralization of such acid waters. Where other buffers are sufficient to maintain pH in an alkaline range, the sulfide resulting from sulfate reduction represents an energy source for carbon fixation by chemotrophic bacteria in a form which should be useful to the aquatic food chain [58].

SUMMARY

The type and amount of aquacultural product is dependent on the type and amount of aquatic photosynthesis in those ponds to which outside foodstuffs are not added. The type and amount of aquatic photosynthesis is determined by interactions between available light, pond morphology, local temperature, the alkalinity and nutrient content of the water, the animal community present, and detention time of the water in the pond. Since many of these parameters are dictated by local land use and geological and climate conditions peculiar to the drainage basin of individual ponds, it is neither particularly instructive nor worthwhile to attempt generalization of aquacultural potential of a large region without a good bit of base data from specific sites. Rather, emphasis should be aimed at developing an understanding of the exact mechanisms associated with the biological, chemical, and physical factors which interact and feedback to set limits on the ability of freshwater systems to produce products of value. An understanding of these ecological limits would allow better design and operation of aquaculture systems in a manner tailored to fit local environmental constraints on a worldwide basis.

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FISH/PLANKTON INTERACTIONS

by

Eugene Leslie Torrans

INTRODUCTION

The conversion of solar energy to chemical energy (carbon compounds) by phytoplankton is the essential first link in most aquatic food chains. Phytoplankton is collected and utilized by the primary consumers (zooplankton) which serve as a major food source for a wide variety of organisms, including fish. The biomass of zooplankton in intensively-managed static-water culture ponds normally ranges from 2 to 20 g/M^3, and can be as high as 2 kg/M^3 in localized areas for short time periods (Table 1). The biomass of phytoplankton is usually several times higher than the zooplankton.

UTILIZATION OF PLANKTON BY FISH LARVAE AND FRY

The lack of fish fry or fingerlings is often a major constraint to developing a successful "grass roots" aquaculture program in many LDC's (lesser developed countries). Well-trained extension agents could alleviate this problem by establishing private (village-level) sources of fish such as the tilapias (=Saurotherodon spp.). This method is by far more cost-effective than centralized government hatcheries. However, the spawning of many popular species of cultured fish requires special facilities and a degree of sophistication that may not be available at the village level. A government facility or skilled private producer is usually necessary to provide the fry of these species.

Table 1

ZOOPLANKTON STANDING CROP IN FISH PONDS

Nutrient input	Dominant organism by mass	Zooplankton standing crop, g wet weight/m^3
Nitrogen-phosphorous fertilizer [57]	Cladocera	0.4-13.1
Nitrogen-phosphorous fertilizer [99]	Cladocera	6.2-13.02
Mineral fertilizer and feed [45]	Cladocera/rotifers	2.8-17.0
Phosphorous/nitrogen chemical waste [85]	Cladocera	329
Organic fertilizer and feed [93]	Zooplankton	10-2000

This high plankton biomass is an undesirable by-product of the intensive culture of channel catfish in the U.S., and necessitates both aeration and dilution to maintain good water quality. However, in most other areas of the world, plankton provide a tremendous food source for a variety of planktivorous fishes. A thorough understanding of fish/plankton interactions can lead to management practices that could greatly increase fish production. The intention of this paper is to summarize the current knowledge and practices involving fish/plankton interactions, and to indicate areas that could bear further examination.

Hatching success and subsequent fry survival (especially of many cyprinid species) are extremely variable, ranging from 0 to nearly 100%. Poor hatching success, or failure of the fish to spawn at all, may be due to a variety of factors, including:

(1) crowding and/or poor nutrition of brood stock

(2) immature brood stock

(3) hormone injections and forced ovulation of "green" fish or fish that have begun to reabsorb the eggs

(4) physical stress on brood fish

(5) poor water quality in spawning ponds

(6) failure to maintain proper physical/chemical water quality for development of fertilized eggs and fry.

However, even with a viable spawn and good hatching success, the gradual loss of fry can result in 100% mortality. This gradual loss is known as the "dwindles" and is largely related to the abundance and type of food available to the fry, as well as the presence of both planktonic and insect predators of the fry.

Larval Food Requirements

Most fish go through a post-hatching developmental period similar to that described for the grass carp (Ctenopharyngodon idella) [2]. At hatching, the pre-larvae are motile, pigmentless, and obtain nutrients entirely from the yolk sac (endogenous feeding). The pre-larval stage lasts from two to five days, depending upon water temperature, and during this period pigmentation develops as do the various other structures. Upon completion of the pre-larval stage, the highly motile larvae are capable of ingesting food:

Larval Stage I - Mixed (endogenous-exogenous) feeding of the larvae

Larval Stage II- Feeding of the larvae exclusively on external food (exogenous).

Successful feeding during this early stage of development is essential for larval survival [82]. Although cyprinids can survive extended food deprivation (silver carp larvae can withstand 10 days of starvation), larvae that are starved for the first few days may never learn to feed, even if they are subsequently supplied with abundant food [55]. Thus, it is imperative that larvae successfully feed at this early stage so as to mature and develop a normal feeding behavior.

Since larvae need food items that are visible, suspended in the water, small enough to be ingested, nutritious, and palatable, it is no surprise that larvae of most fish feed initially on zooplankton. Although smaller phytoplankton and larger zooplankton may be important first food for some species [3,31,49,73,75], rotifers, copepod nauplii and copepodites, protozoa and small cladocera in the 50-200 u range are the predominant first foods of most species (Table 2).

Food Selectivity

Larvae and fry of most species are visual particulate feeders, catching and consuming individual prey items. A typical feeding sequence would involve 1) searching the visual field to locate prey items, 2) fixation on prey item and approach, 3) attack on prey by biting or snapping aided with suction from the buccal pump to draw the prey item in, and 4) acceptance or rejection of the item based on size, texture and taste. While chemo-senses are used to evaluate captured prey items, they are apparently not used to locate prey by most species of fish larvae or fry [61].

While searching behavior may be random, there is often a definite selection of particular items from a mixed prey population. This is usually expressed as Ivlev's Electivity Index, $E = \frac{ri - pi}{ri + pi}$, which compared the relative abundance of food items in the intestine (ri) to those in the water (pi) [29]. The values of E range from -1.0 (total avoidance) to +1.0 (total selection).

Food preference and feeding success of fish fry are determined by a combination of several biological and physical factors:

Prey Size Prey size is the major factor controlling prey selectivity by fish larvae and fry. With very small prey items, visual detection is difficult and return/effort of feeding is low. Conversely, there is a maximum size at which prey items can be physically captured and ingested. Fry will usually eat a size range of plankton at a low absolute prey abundance. However, as the prey density increases, the smaller items are sequentially dropped from the diet [96]. Since the reaction distance of fish is generally a linear function of prey size [13,14], and the return/effort is higher when feeding on larger items, fry will usually select the larger items from a mixed prey population. As fish grow, they will usually select progressively larger prey items [4,20,26,84,88]. Rotifers and copepod nauplii and copepodites are in the optimum size range for most stage I-II larvae.

Prey Density Given prey items of acceptable size, larval survival is a function of prey density. The critical level for very limited survival of most fish species is between 30 and 200 prey items/liter (Table 3). Survival usually increases with increasing prey density up to about 1000 items/liter. This appears to be the minimum prey level for good survival of most species. The optimum prey density decreases with increasing prey size within the acceptable size range for the species [17].

Apparently conflicting results are often seen with respect to larval growth and survival as a function of prey size. The survival of silver carp is better with rotifers as prey, while growth is faster with copepods as prey [55,87]. This is explained by the fact that since silver carp initially begin feeding on rotifers, a high rotifer density is necessary during the first 11 days to obtain high survival. At the end of this developmental period, the larvae can consume larger copepods and, in fact, require them for good growth.

Activity Of Prey Prey movement will increase the chances of visual detection by fish larvae. However, zooplankters capable of very strong swimming may avoid capture by the particulate (suction) feeding larvae [39]. The probability of being captured by a simulated fish-suction intake ranges from P=0.76 to P=0.96 for cladocera, and only P=0.07 to P=0.28 for copepods [22]. Since copepods are negatively rheotactic and stronger swimmers, their

Table 2

FIRST FOOD OF VARIOUS CULTURED AND NON-CULTURED FISH SPECIES

Fish species	Fish age/size	Food item
Aristichthys nobilis (bighead carp)	Stage II	Phytoplankton
	Stage III	Rotifers & copepod nauplii
	Stage IV	Copepodites & small cladocera (51)
Tilapia nilotica	Fry	Rotifers, copepods, detritus aufwuchs, hydracarines (64)
Hypophthalmichthys molitrix (silver carp)	-----	Rotifers (55)
	5 days	Phytoplankton & zooplankton (71)
Ctenopharyngodon idella (grass carp)	4-5 days/6-8 mm	Rotifers (50-150 μ) (88)
Cyprinus carpio (Common carp)	4-5 days/6-8 mm	Rotifers (50-150 μ) (88)
	1-3 days	Copepod nauplii (18)
Catla catla	Larva & young fry 1-15 days	Phytoplankton (34) Cladocera, rotifers, Copepods (11)
Labeo rohito	1-15 days	Nauplii & copepodites (11)
Cirrhina mrigala	1-15 days	Nauplii & copepodites (11)
Puntius pulchellus	18-23 mm	Zooplankton (19)
Micropterus salmoides (largemouth bass)	15 mm	copepods & cladocera (74)
Sea bream	3 days	Nauplii, copepodites & copepods < 100 u (84)
Green back gray mullet	< 12 mm	Zooplankton (12)
Black sea turbot	-----	Rotifers (82)
Mullet (12 species)	10 mm	Zooplankton (5)
Chanos chanos (milkfish)	Fry	Phytoplankton (34)

successful avoidance of fish predators may result in an apparent selection for cladocera by fish larvae.

Larval Movements Movement of fish through water increases the frequency of prey encounters. For example, whitefish larvae search a total of 188 liters of water in a 10 hour daylight period, consuming 60 to 216 organisms/day [17].

Light/Turbidity Larvae of most fish species are diurnal visual particulate feeders [4,10,26]. These larvae will commence feeding in the morning, with both the percent of feeding fish and the number of organisms in the larvae's stomach increasing during the day [50]. The peak feeding time for silver carp is 1300 hours [71]. High turbidity will reduce the feeding rate, but the prey size selected by fish appears to be independent of turbidity.

Transparency Of Prey Because fish larvae are visual feeders, the increased transparency of prey reduces capture success [27,100]. However, this may not be as important in practical situations as prey size is in determining the selectivity and capture efficiency of fish larvae.

Utilization of Plankton by Larvae and Fry

Zooplankton are high in protein and essential amino acids [76], and are easily digested. Fry normally consume 40-80% of their body weight daily [26,84], assimilating from 89-98% of the ingested food [58,70]. Larvae and fry will usually feed throughout the day, digesting a food batch in 3-5 hours [82]. The rate of digestion varies, e.g., cladocera are digested much more rapidly than copepods. The relative rates of digestion may result in erroneous

Table 3

EFFECT OF PREY DENSITY ON SURVIVAL OF LARVAL FISH

Species	Prey item	Prey density	Results
Bay anchovy	Copepod nauplii	50/L	6% survival (35)
	Copepod nauplii and copepodites	107/L	10% survival (36)
	Copepod nauplii	1000/L	43% survival (35)
Lined sole	Copepod nauplii	50/L	2% survival (35)
	Copepod nauplii and copepodites	130/L	10% survival (36)
	Copepod nauplii	1000/L	48% survival (35)
Sea bream	Copepod nauplii and copepodites	34/L	10% survival (36)
Atlantic Cod	Rotifers, nauplii and copepodites	200/L	Died in 12-13 days (9)
	Rotifers, nauplii and copepodites	1000/L	Protein increased 9.3%/day (9)
Black sea turbot	Rotifers	100-1000/L	No change in feeding within this range (82)
Whitefish	Cyclops sp	200-260/L	Optimum (17)

estimates of food selectivity due to the more rapid disappearance of certain species from the gut [24].

The outstanding qualities of live plankton (movement, size, protein content, palatability, digestibility) are impossible to match with an artificial ration. Although a wide variety of feeds have been tried [11,18,28,42], all have resulted in either increased mortality (due to poor acceptability by fry) or decreased growth rate (due to nutritionally incomplete diets) when compared to live plankton.

With the present state of the art, it is nearly impossible to rear larvae and fry entirely on an artificial ration. However, artificial (non-plankton) food may be useful during two developmental stages:

1) When eggs are hatched in artificial containers, it is often advantageous to feed the larvae before releasing them into the pond. If they are to be fed for only a day or two, hard-boiled egg yolk, crumbled and dissolved in the water, has been found to be satisfactory [28].

2) Once the fry have begun to grow on the natural plankton in the pond, they may be gradually trained to take a supplemental feed if the particle size is acceptable.

Management of Fry Ponds

The zooplankton biomass in a well-fertilized culture pond may be as high as $2kg/M^3$ [93] yet the survival and growth of the fry may be very poor. This is the result of two interrelated factors:

1) The size structure of zooplankton in an established population may be biased in favor of the larger cladocerans and copepods. If sufficient small plankters (in particular rotifers and nauplii) are not present, larvae and fry may starve in an abundance of larger zooplankton. Those that do survive grow faster once they are able to consume these larger organisms.

2) A high density of large predaceous copepods can reduce larvae and fry numbers directly through predation.

Both these problems can apparently be eliminated by treating a pond with Dylox (=foschlor, flibol, neguvon, dipterex, trichlorophon) or Baytex several days prior to stocking. When properly applied at the correct dose, this organophosphate kills crustaceans without harming rotifers [87]. A week or two later, the ponds can be innoculated with cladocera to promote the growth of advanced fry [88]. Applications of quicklime (CaOH) at 500-1500 kg/ha may have a similar inhibiting effect upon the crustacean zooplankton [46].

Areas for Future Research

Although many basic interactions between fish larvae and/or fry and plankton are well understood, details are lacking for most of the fish species cultured worldwide. To correct this situation, specific

information should be obtained relating to the preferred first foods, optimum prey density, and changes in food habits during the early development of these species. The techniques of fry pond management can then be "fine tuned" to greatly increase fingerling production. The development of a simple, nutritionally complete, palatable fry food would be a boon to production of fry requiring artificial hatching, particularly the cyprinids.

UTILIZATION OF PLANKTON BY ADULT FISH

The predominant food of nearly all larval fish is zooplankton, in particular, rotifers and smaller crustaceans. However, the food habits of different fish species rapidly diverge during the early life history (Table 4). While some species retain planktivorous habits [23,32,38,51,71] others turn to larger animals [74], vegetation [19,34] or varying degrees of omnivory [34,43,56]. Early divergence of food habits, together with differences in habitat selection, plays a vital role in reducing competition for food, both within and among species.

Planktivorous fish have numerous long, closely spaced gill rakers that act as a sieve to filter water and trap plankton. To compensate for the increased spacing that occurs with growth, the gill rakers of some species develop either secondary projections or microspines, which keep the pore size relatively small [30,83,91], or they develop a series of micro-gill rakers at the base of the gill filaments [97]. Silver carp have the most specialized gill raker system of any fish presently being cultured. When the fish are only 26 mm long, the gill rakers fuse together to form a net [30]. The gill rakers are completely fused together in adult fish and are comprised of two layers: an internal straining portion of fine filaments and an external thicker support [98]. The gill raker net has pores less than 20 u in diameter, allowing adult silver carp to capture smaller particles than fry can.

A large number of species have a more limited filtering capacity. These facultative planktivores are able to subsist on plankton when there is a high density of relatively large plankters. When plankton is limited, they readily consume other items [83,90].

Table 4

AGE-RELATED CHANGES IN THE FOOD HABITS OF FIVE SPECIES OF CULTURED FISH

Species	Size	Food habits
Micropterus salmoides [74]	5-10 mm	Copepods and Cladocera
	15 mm+	Midge larva and pupae
Labeo rohita [43]	fingerling (< 100 mm)	Zooplankton, some phytoplankton
	adults (> 300 mm)	Phytoplankton, macro-vegetation organic matter
Aristichthys nobilis [51]	Stage II	Phytoplankton
	Stage III	Zooplankton
	Stage IV	Larger plankton
Hypophthalmichthys molitrix [71]	Stage II	Phytoplankton
	Stage III-V	Zooplankton
	1 month	Phytoplankton
Putius pulchellus [19]	18-22 mm	Zooplankton
	30-50 mm	Decaying plant, leaves, filaments, algae, diatoms
	305-705 mm	Aquatic vegetation

Feeding Structures

The development of various types of feeding and digestive structures, particularly the gill rakers, epibranchial organ and lengthening of the intestine are indicative of planktivorous food habits in the adult.

Gill Rakers The morphology of the gill rakers is an obvious indication of a fish's feeding habits. Most carnivores, herbivores, and omnivores have few, relatively short gill rakers. Although they particulate feed on plankton as juveniles, as they increase in length, spacing between the rakers increases to the point that they can no longer effectively trap plankton. Large individual plankters may still be utilized, but for the most part, such fish turn to larger sized food items.

Epibranchial Organ The epibranchial, or palatal, organ is a downgrowth from the roof of the pharynx. Covered with both taste buds and mucus cells [91], it partially occludes the buccal cavity and is useful in the selection, capture and manipulation of plankton trapped by the gill rakers. Many planktivores have some type of palatal organ [48,91], but the highest degree of development appears in the silver carp [6,98].

Lengthening Of The Intestine Most planktivores have a high intestine length/body ratio, particularly those that feed at least in part on phytoplankton [98]. This is viewed as an adaptation for the digestion of plant material. While in most species the length of the intestine increases gradually with age, the intestine

of the milkfish (Chanos chanos) undergoes heteronomous growth [31].

Feeding Behavior

Planktivorous fish utilize a variety of feeding mechanisms to capture plankton, depending on prey size and density. The northern anchovy (Engraulis mordax) captures Artemia adults (3.7 mm long) by biting (particulate feeding) and nauplii (0.65 mm long) by filter feeding. Feeding activity is half biting and half filtering when Artemia adults comprise 2% of the total plankton biomass, and is entirely biting when adult Artemia exceed 7% of the prey biomass [69].

Threadfin shad (Dorosoma petenense) likewise utilize both particulate and filter feeding. Small particles (<0.39 mm) are filtered while larger items are taken individually. Particulate feeding decreases with decreasing light intensity, and is not possible with less than bright moonlight. However, shad can filter feed 24 hours a day, using chemosenses to locate prey [61].

Alewives (Alosa pseudoharengus) employ three modes of feeding: particulate, "gulping", and filtering [38]. The mode employed depends upon prey size, prey density and fish size. Larger prey elicit size-selective particulate feeding. As prey size decreases and prey density increases, alewives employ "gulping" (slightly size-selective) and filter feeding (not size-selective). Filtering is more common with large individuals of this species at high prey densities, while particulate feeding is typical of the smaller individuals.

Food Selection

The specific feeding method used by a fish (and the food it ingests) is a combination of that species' functional morphology, the light intensity, and the density and composition of the plankton. The food actually taken by a fish may not, in fact, reflect the preferred food of that species, but rather the most energy efficient method of nutrient intake given the actual availability of food in the environment (Table 5).

Amidst an abundance of plankton, the food items selected by a planktivorous species can be predicted on the basis of the morphology of its feeding structures. Silver carp graze primarily on phytoplankton in the 8-100 u size range [16,80,98], while bighead carp select zooplankton and larger phytoplankton in the 17-3000 u range [16,67]. Most planktivorous fish show a positive selection for larger prey items within their acceptable size range [1,8,13,14,15,21,23,37,68,94,95,96]. This is advantageous since feeding on larger organisms is usually more energy efficient. However, in cases of very low plankton biomass, even supposedly stenophagous planktivores will take a variety of foods, including detritus, plant materials, supplemental food and small fish [16,44,51,56,71,81]. The degree of omnivory varies considerably among species, and may play a large role in the success of some species [8,47].

Filter feeding planktivores normally have a daily feeding period with a peak in late afternoon [65,67,71]. The total amount of food consumed daily by a planktivore is affected by a combination of factors: temperature, size of fish and plankton, density and species composition of the plankton. The daily food consumption of planktivores is normally 10-20% of the body weight [66,67,92]. However, the food intake of the silver carp may be as low as 1-3% when the plankton concentration is low [80], and they may cease feeding altogether when there are dense blooms of blue-green algae [40].

Assimilation Of Plankton

The digestibility of plankton is extremely variable, ranging from 43-89%, depending upon the fish species and the plankton composition [24,64,65,70]. The food conversion efficiency (weight of food eaten to weight of fish produced) of planktivores normally ranges from 5:1 to 18:1 on a wet weight basis [67,70], but the digestibility of various plankters varies considerably among the planktivores [75].

Silver carp are unable to digest blue-green algae, while Tilapia nilotica can assimilate from 70-80% [40,63,65,81]. The high assimilation of blue-green algae by T. nilotica is made possible by the secretion of a stomach acid, which lyses the algal cells. The acid secretion follows the feeding cycle, increasing during the day. Assimilation of blue-green algae is greatest at the end of a feeding period, when acid concentration is greatest and the food retention time is longest [63,65]. Other fish species that consume and digest blue-green algae, such as the milkfish and the mullets, may likewise use acid secretions to lyse algal cells [63].

Although planktivores' intestines are long relative to body length [16,31], a plankton food batch may pass through an adult fish in as little as 5-8 hours [67]. This rapid digestion of plankton complicates feeding studies of planktivores.

Grazing by planktivorous fish can cause a tremendous decrease in the density and composition of the plankton community [72,78]. Selective predation on zooplankton may result in up to a 75% decrease in zooplankton biomass [90] and an increase in the phytoplankton [1].

In a fish-free system, the larger crustacean zooplankters are usually dominant over the smaller organisms, both through competition for food and direct predation. A planktivorous fish that selects larger organisms can result in increases and dominance of the smaller zooplankters [10,15,21,37,68,95]. Thus, size-selective predation results in a major change in plankton species and size distributions.

Research Areas

Although the dynamics of the predator-prey system of fish and plankton has been extensively studied by aquatic ecologists in natural systems, most studies in warm-water culture ponds have been limited to particle size or species selection as reflected in stomach contents. Detailed investigations of the filtering efficiency (% retention of plankton/volume filtered) of commercially cultured fish are lacking, as in information on the digestibility and food conversion efficiency of various plankton/detritus diets. We must understand the comparative capture, conversion and

Table 5

FOOD HABITS OF ADULT PLANKTIVOROUS FISH

Species	Food habits
Aristichthys nobilis	Zooplankton, suspended organic substances [67] Zooplankton, up to 82-98% detritus [51] 67% phytoplankton in cages, 69% detritus in ponds [16]
Hypophthalmichthys molitrix	Phytoplankton < 20 u [80,98] 84% phytoplankton, 15% detritus [16] Phytoplankton, zooplankton [67] 10-60% phytoplankton, 10-30% zooplankton [40] 90% detritus [71]
Chanos chanos	"Lablab" in Philippine ponds [54] Diatoms in Hawaiian ponds [31]
Tilapia nilotica	Phytoplankton [64,65,66] Blue-green algae [63] Zooplankton; detritus at times of low zooplankton biomass [81] Filamentous algae [56]

growth efficiencies of common planktivorous fish in order to maximize the flow of energy from plankton to edible fish flesh. Energy flow models that are developed should not be based entirely on academic ideas, but must be tempered by practical consideration, i.e., large-scale availability of fingerlings, suitability of the chosen species to local culture techiques and marketability of the final product.

APPLIED ASPECTS

In most areas of the world, primary agricultural products are in such high demand for direct human consumption that their use as a supplemental fish food is precluded. In addition, large areas of the world, primarily Africa, have no cultural tradition in confined livestock feeding, using instead the open range. Even small animals, such as chickens and goats, are allowed to forage for their food. Thus it is difficult, even where limited quantities of agricultural or domestic by-products are available, to train rural farmers to feed their fish.

However, since fish forage for natural food, it is somewhat easier to convince rural farmers to fertilize their ponds to increase the natural food for the fish. Fertilization is the most cost-effective means of increasing fish production since it requires only a periodical, rather than daily, effort. The most efficient means of converting this natural food to fish flesh is through primary or secondary consumers (planktivorous fish). There is a strong correlation between fish production and primary productivity [7,41,53,59,60,79], which explains the worldwide popularity of fish that are primary and secondary consumers.

The application of fertilizer to ponds stocked with fish that feed low on the food chain (milkfish, common carp, silver carp, bighead carp or Tilapia nilotica) may increase the production from two to ten times over unfertilized ponds [33,41,52,62,77]. Production from 1500 to over 6000 kg/ha•yr is possible using only fertilizer (primarily organic manure) as the energy input. Fish yields can be increased in three ways without feeding.

Add organic fertilizer to increase both primary productivity and the carrying capacity of the pond Fish production increases linearly with organic input up to the point that water quality becomes limiting for the species being cultured [33]. Tilapia nilotica and common carp are both very tolerant of poor water quality (particularly low dissolved oxygen) and respond well over a wide range of organic loading. Fertilization is usually the easiest means of increasing production, but the type, quantity, frequency and method of application of the organic manure must be considered to maximize returns.

Reduce the length of the harvest cycle Fish stocked in a pond (assuming there is enough, and/or that there is reproduction) will eventually grow to reach the carrying capacity of the pond. The carrying capacity is largely determined by the nutrient input, the water quality and the fish species being cultured. Fish that are acceptable to consumers at a smaller size can be stocked at very high rates and will reach the carrying capacity sooner, allowing a farmer to get several complete harvests in a year. This is presently being done in the Philippines, where Tilapia nilotica of 50-100 grams have good consumer acceptance (personal observation). Farmers there stock 20,000 fry/hectare in fertilized ponds and harvest 1000-2000 kg/ha in three months. The annual production thus ranges from 4-8000 kg/ha, remarkable for monoculture in non-fed ponds. In addition, since the fish are harvested before reproduction gets out of hand, all the fish are of marketable size, thus eliminating the major problem with tilapia culture.

Polyculture Polyculture is the rearing together of more than one fish species (sometimes as many as six or seven) in a pond. In theory, several species (each with slightly different food habits) will more

fully utilize the natural food in a pond, resulting in increased production. Often supplemental feed is given to one or more of the species (usually the grass carp or common carp) to provide the energy subsidy that drives the system. This culture system is well established in Asia. In Taiwan, silver carp, gray mullet, bighead carp, grass carp, common carp, black carp and sea perch are stocked together. In other areas, various other cyprinids (Labeo spp., Catla catla), Tilapia spp., and predatory species, such as Clarias spp. or Ophiocephalus spp. are sometimes used. In Taiwan, the stocking rates presently used are the result of many years of experience, and are based on the amount of food available to each trophic level of fish [89]. With large energy subsidies, this system can result in fish production of from 6000-8000 kg/ha•year.

While polyculture is well established and very successful in parts of Asia, it cannot (and perhaps should not) be applied to other areas in the world that are struggling to start an aquaculture program. In many areas of the world, both the private and government infrastructures are so poorly developed that it is difficult for farmers to get even fingerlings of Tilapia nilotica, a very prolific fish. The establishment of a dependable supply of one or two other species would be a monumental undertaking, and may not be advisable. Where the need for aquaculture is the greatest, very small fish usually have high consumer acceptance. In these areas, tilapia can be stocked heavily and harvested in a few months (as opposed to a 12 month harvest cycle for most cyprinids), resulting in an annual production as high as the Chinese polyculture system. This may not be glamorous, but is probably the most efficient means of producing a large volume of high quality fish for a protein-starved people.

Once the private sector has successfully grasped the basic principles of fish production (fry production, stocking, fertilization, feeding, harvesting and sale), a two-species approach may be useful. A planktivorous species is used (Tilapia nilotica or the silver or bighead carp) to graze on plankton [16,33,62,67,86], and an omnivore/detritivore is added (usually the common carp) which feeds upon and recycles organic detritus from the pond bottom. In this situation, the growth of both species will probably be better than when either is raised alone [77].

Research Areas

The local geographical, cultural and political constraints should be fully understood before beginning an aquaculture research program if the program is to have any effect on the private sector. It may do more harm than good if a highly productive but elaborate scheme is developed at a government research center that cannot be applied by the private farmers due to local constraints. Too often, techniques or programs are proposed in LDC's by expatriate advisors because they are effective in the U.S., and not because they are needed in that country.

SUMMARY

The constraints to fish production vary considerably among LDC's. In most areas of the world, particularly in Africa, the most serious problem is not a lack of technology but the transfer of the existing technology to the rural farmers. The lack of trained personnel, poor communications and the limited resources of fisheries departments in LDC's accounts for most of the disparity between the known and applied technology. In other areas, however, private farmers are applying the current state-of-the-art and are limited by basic research and development.

The stated goal of the Title XII Aquaculture CRSP is basic research and development on state-of-the-art constraints to fish production in LDC's. This is necessary for any industry to achieve maximum growth, but it must be complemented with a grass-roots extension program if it is to have any real impact on the private sector. In addition, basic R & D should employ appropriate technology so results can be easily transferred to the private sector.

The following is a non-prioritized list of research topics concerning fish/plankton interactions. The relative necessity for basic research on any of these topics will be determined by local cultural, geographical and technical considerations.

1. Preferred first food of fish larvae and fry.
2. Prey density necessary for optimum larval and fry survival.
3. Predation on fish larvae and fry by zooplankton.
4. Management of plankton populations in fry ponds (fertilization and chemical treatments).
5. Development of a complete ration for larvae and fry.
6. Changes in food selection with fish age/size.
7. Feeding mechanisms (histological, morphological and behavioral adaptations) of adult planktivores.
8. Species and particle size selection of adult planktivores.
9. Feeding efficiency (water volume filtered and capture efficiency) of planktivores.
10. Assimilation of plankton by fish (digestibility, assimilation and conversion of various plankton diets as affected by the species and size of fish).
11. Effect of fish predation on plankton populations.
12. Energy-flow diagrams for pond systems with various nutrient inputs and fish stocks --least-cost fish production based on locally-available inputs.

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PART 3

POND CULTURE PRACTICES

POND PRODUCTION SYSTEMS: STOCKING PRACTICES IN POND FISH CULTURE

by

Yung C. Shang

FOREWORD

Pond management practices vary not only between species but also between different socio-economic and cultural settings. In this and the following four papers the purpose is to review and synthesize pond management practices in the areas of 1) stocking, 2) fertilization, 3) feeds and feeding, 4) water quality, and 5) disease and predator control of major fresh- and brackish-water species (e.g., carps, milkfish, mullet, tilapia, and walking catfish), to establish credible guidelines for an effective pond management system.

INTRODUCTION

In aquaculture "stocking materials" (or "fish seed") generally refers to the fry, post larvae, and fingerlings of the species to be cultured. Fish seed are usually obtained from two sources: (1) natural waters, e.g., milkfish, grey mullet (to a large extent), and eel; and (2) hatcheries, e.g., Chinese major carps, Indian major carps, rainbow trout, channel and walking catfish, tilapia, grey mullet (to a limited extent), and snakehead (Shang, 1981).

The term "stocking rate" has a variety of interpretations. In many countries it is defined as the number of fish seed stocked per unit water surface, with due consideration to the size and/or age group of the stocking material. In others, it is the total weight of fish seed stocked per unit water surface regardless of the age groups of the seed (Rabanal, 1968). Various degrees of intergrading these two stocking concepts are encountered in the literature.

FACTORS AFFECTING THE STOCKING RATE OF A POND

One of the most important pond-management practices is the stocking of the appropriate species and quantity of fish. A fish pond can only support a certain quantity of fish because of its limited space and the amount of natural food available. The latter is affected mainly by the soil conditions and water quality of the pond. This limit is usually called the carrying capacity (or maximum standing crop) of the pond. It is defined as the maximum weight of fish stock that can be sustained by a pond (by either the food produced within the pond or made available to the fish) without gaining or losing weight (Hickling, 1962). The carrying capacity of a pond can be increased by fertilization and/or supplemental feeding. The purpose of fertilization is to increase the production of plankton or benthic algae as fish food, while supplemental feeding compensates (directly or indirectly) for nutrients which are in short supply in the pond. In Israel, fertilization increased the carrying capacity of carp ponds almost fourfold and fertilization and supplementary feeding increased it 10-15 times (Yashouv, 1959; Hepher, 1978).

Van der Lingen (1959) revealed that the maximum standing crop of tilapia cultured in Rhodesia is about 2.5 times higher in fertilized ponds (and about seven times higher in fertilized ponds with supplemental feeding) than under natural conditions. Tang (1970) estimated that a heavily fertilized pond in Taiwan produces ten times the amount of phytoplankton and zooplankton than an unfertilized reservoir produces. Shang (1976) indicated that the stocking rate (and hence the total yield) in intensively managed milkfish ponds (with fertilization and/or supplemental feeding) in Indonesia and the Philippines is about 3-4 times higher than that of extensively managed ponds.

Aeration and running-water systems usually increase the amount of dissolved oxygen and, therefore, increase the carrying capacity of a pond. For example, in the running-water ponds of the Philippines, common carp fry are stocked at rates of 280,000 to 850,000/ha as compared to 50,000/ha in still water (Bardach, et al., 1972). Kawamoto (1957) and Chiba (1965) have shown that the yield and growth of carps in ponds with running water is 100 to 1000 times higher than in ponds with still water because of the elimination of growth-inhibiting metabolites and the continuous supply of oxygen. Basing his study on common carp culture in several countries under different management systems, Hepher (1978) demonstrated that the stocking rate and the yield/ha increased with fertilization, supplemental feeding, and running water systems.

A further increase in the stocking rate of a pond can be achieved by polyculture (stocking a number of species in the same pond) and by stock manipulation (methods used to manage the fish population in the pond).

STOCKING PRACTICES

A sound stocking technique is to balance fish populations with fish foods available in the pond. To estimate the right stocking rate requires basic information on the quality and quantity of natural foods available in a given period of time as well as the feeding rate of the different age (or size) groups of the species concerned. This sort of information varies and is not always available. The most widely used stocking technique is based on common sense and experience, as shown in the following formula:

Number of fish to be stocked =

Size of fish pond (ha) x expected yield (kg) per ha based on experiences of previous years

Expected average weight of individual fish when harvested - Average weight of individual fry or fingerling when stocked

+ expected mortality (no.) + additional number of stocking due to fertilization and feeding.

The estimated stocking rate with fertilization and feeding is respectively based on the additional amount of natural food available in the pond and the food conversion ratio (units of feed to produce one unit of fish).

Based on this empirical stocking method, several fish-stocking practices of varying complexity have been used for various species in different regions. These stocking practices may be divided into two management systems: monoculture and polyculture.

Monoculture

Monoculture, which is practiced in many countries, is the stocking of a single species in a pond. Within a monoculture system, there are several stocking practices that affect the fish production of a pond.

Mono-size Stocking This is simply to stock one species of the same size in a pond and to harvest all the fish at marketable size. This practice has some disadvantages. If stocking density is too great, the fish would be overcrowded when they reach adult size. Thus growth and survival rates would be reduced. On the other hand, if stocking density is low, the water space and the natural food in the pond will not be efficiently utilized during the earlier part of the rearing period. Understocking is a common practice. For example, many extensive milkfish operators in Indonesia and the Philippines use low stocking densities and, as a result, achieve only a low level of production (Shang, 1976). A recent production function analysis of the milkfish industry in the Philippines based on cross-section data revealed that a 0.6 percent increase in milkfish production can be expected with every one percent increase in the fry stocking rate (Chong, et al., 1981).

Fry rearing in nursery ponds usually uses mono-size stocking practice. The stocking rates of fry for various species in different countries are summarized in Table 1.

Multi-stage Stocking An alternative stocking practice that avoids the disadvantages mentioned above is multi-stage stocking, where fish of uniform size are stocked in progressively larger ponds as more space is needed. This method takes advantages of the maximum growth potential of the fish; their density can be adjusted as they are transferred to larger ponds. The smaller ponds are then prepared for the rearing of succeeding batches of younger fish. This enables the farmers to undertake a continuous cycle of stocking and harvesting. This stocking method has been practiced by some milkfish farms in the Philippines with encouraging results (Tang, 1972; Rabanal, 1968). However, it can only be practiced by relatively large-scale operations with several pond units. An example of multi-stage stocking is presented in Table 2.

Multi-size Stocking This practice also avoids the stocking density problems of mono-size stocking. Fish ponds frequently produce a variety of fish food, and the feeding habits of the young and adult fish are often quite different. Consequently, the stocking rate (and, hence, the total yield of a pond) can be increased by stocking different age groups of a fish species to more efficiently utilize the available forage. This practice requires periodic harvesting of the marketable-size fish. The pond may then be restocked with smaller fish to replace the ones removed. A typical example of this stocking practice (in the milkfish culture in Taiwan) is shown in Table 3.

The initial stocking of the ponds in April involves fingerlings of sizes varying from 5 to 100 g in weight at about 5,000 fish/ha. Fish harvest begins at the end of May and at least eight harvests are made until the middle of November. Stocking of newly captured fry is made from April to August. The new fry stocked in July (and after) do not reach marketable size by November and are put into wintering ponds for next year's stocking. Under this management system, a total of 15,000 fish can be stocked per ha with an annual yield of more than 2,000 kg of marketable fish. The high yield of milkfish ponds in Taiwan, when compared to those in Indonesia and the Philippines, may be attributed to the use of multiple-size stocking. This practice has been adapted for use in other countries for both fresh- and brackish-water culture.

Monosex Stocking The major problem of culturing a species such as tilapia, which reproduces in the rearing pond, is that the pond will soon become overpopulated with small unmarketable fish. One way to solve this problem is to stock a single sex of the species. In this case, no reproduction is possible.

Double Cropping This is the practice of stocking two species in the same pond but in different seasons to take advantage of their different thermal requirements. The stocking of channel catfish during the summer and rainbow trout during the winter in the United States increases the total production and profit of a pond (Brown, 1979).

Table 1

STOCKING RATE OF FRY BY COUNTRY AND SPECIES

Country and species stocked	Stocking rate, no. of fry/ha	Age or size	Source
JAPAN			Bardach, et al., 1972
Common carp	3,000-15,000	Fry	
Grass & Silver carp	1,400-1,800/m^2	10-20 mm	
INDONESIA			
Common carp	60,000	3 wks. old	Bardach, et al., 1972
Milkfish	300,000	Fry	Korringa, 1976
PHILIPPINES			
Common carp	50,000	8-10 mm	Bardach, et al., 1972
Milkfish	30-50/m^2	Fry	Korringa, 1976
TAIWAN			
Chinese carp	300,000/0.1 ha	Fry	Chen, 1976
	70,000-80,000/0.1 ha	2-3 cm	
Milkfish	70,000-150,000	Fry	Korringa, 1976
ISRAEL			Bardach, et al., 1972
Mullet	10,000-20,000	Fry	
USA			Bardach, et al., 1972
Common carp	250,000 (experimental pond)	3-4 wks.	
Catfish	3,300-4,400	Fingerlings	
	1,650-2,200	Fingerlings	
	6,000-110,000 (running water)	Fingerlings	
USSR			Bardach, et al., 1972
Common carp	10-80/m^2	Fingerlings	
INDIA			Bardach, et al., 1972
Common carp	1.25×10^6 - 2.5×10^6	2 days old	
CHINA			FAO, 1979
Grass carp	20,000/0.066 ha	3 cm	
	4,000-5,000/0.066 ha	4.8 cm	
Bighead	15,000/0.066 ha	3 cm	
	4,000-6,000/0.066 ha	6 cm	
Mud carp	27,000/0.066 ha	3 cm	
	9,000/0.066 ha	5.8 cm	
Silver carp	20,000/0.066 ha	3 cm	
	800-1,000/0.066 ha	6-9.5 cm	

The stocking rates (based on the available information) in monoculture systems by species and by country are summarized in Table 4.

Polyculture

A fish pond, especially a freshwater pond, usually produces a variety of food organisms in different layers of the water. Therefore, stocking species (or different size classes of a given species) that have complementary feeding habits or that feed in different zones will efficiently utilize space and available food in the pond and increase total fish production.

Polyculture originated in China thousands of years ago and has been improved with the passing of time. It is the practice of polyculture that enables Chinese fish culturists to achieve high productivity per unit area. To assure efficient use of a given pond ecosystem, Chinese fish culturists usually polyculture the following fish: (1) the grass carp (Ctenopharyngodon idellus) which roams in all strata of the water and feeds mainly on higher aquatic plants; (2) the silver carp (Hypothalmichthys molitrix), a midwater dweller that prefers phytoplankton as food; (3) the big head carp (Aristichthys nobilis), also a midwater dweller, which consumes zooplankton; (4) the black carp (Mylopharyngodon piceus), a bottom-dwelling carnivore that feeds on mollusks; and (5) the

Table 2

A TYPICAL CASE OF MULTI-STAGE STOCKING OF MILKFISH PONDS OF DIFFERENT SIZE[a]

Stages of growing	Ponds required			Initial stocking rates			No. of days cultured	Expected population at the end growing stage	
	Size, ha	No.	Total area, ha	No/ha	No/kg	Kg/ha		No/kg	Kg/ha
Stage I	1.0	1	1.0	18,000	400	45	42	50	360
Stage II	3.0	1	3.0	6,000	50	120	46	13	480
Stage III	3.0	3	9.0	2,000	13	160	56	3	650

[a] After Tang, 1972

mud carp (Cirrhinus motilorella), a bottom-dwelling omnivore that feeds on benthic animals and detritus. Other fish often reared with the Chinese carps are common carp (Cyprinus carpio), grey mullet, tilapia, and bream (Parabramis pekinensis). Grass carp is the major species usually stocked when plants are abundant in the pond. In plankton-rich ponds, silver carp and bighead carp are the major species usually stocked. In deeper ponds, the productivity of the bottom water is substantially reduced and the stocking of bottom dwellers is usually low. In cold regions where temperatures rule out the mud carp, other bottom-feeding omnivores like common carp and bream are usually stocked. Various combinations of species used in polyculture in China are given in Table 5.

In other Asian countries, either the above-mentioned species or native fish with similar food habits are stocked. Grass, bighead, silver, and common carps are usually polycultured in Malaysia, Singapore, and Thailand. Mullet and the above-mentioned Chinese carps are polycultured in Hong Kong and the Philippines (Table 6). In these countries, species that are more adapted to colder waters (such as black carp) are not usually raised. The distinctive feature of polyculture stocking in Hong Kong and the Philippines is the use of mullet, which are abundant in those regions.

In Indonesia, native species like tambakan (Helostoma temmincki), tawes (Puntius javanicus), nilem (Osteochilus hasselti), and gourami (Osphronemus goramy), are usually polycultured with common carp and tilapia (Table 7). The tambakan is a plankton feeder, while the tawes consumes coarse pond vegetation, playing the role that the grass carp performs in other countries; the gourami is a herbivore that feeds on softer vegetable materials along the pond margins; the nilem eat plankton, periphyton, and softer or decayed vegetation.

Table 3

A TYPICAL PRACTICE OF MULTIPLE-SIZE STOCKING OF MILKFISH IN SAME PONDS IN TAIWAN[a]

Month of stocking	Approximate average weight of fingerlings stocked, g	Approximate number of fingerlings stocked
April	5-100 g	5,000
May	0.05	2,500
June	0.06	2,500
July	0.06	2,500
Aug-Sept	0.06	2,500
TOTAL		15,000

[a] From Chen, 1976

Table 4

STOCKING RATES IN MONOCULTURE SYSTEMS BY COUNTRY AND SPECIES

Country and species stocked	Stocking rate, No. of fish/ha	Size of fish	Source
PUERTO RICO			Fram, Pagan-Font, 1978
T. nilotica	10,000	15.9 g	
T. horhorum	10,000	53.9 g	
U.S.A.			Bardach, et al., 1972
T. nilotica	20,000 (experimental pond)	-	
Java tilapia	50,000 (experimental pond)	-	
Grass carp	1,700	30-40 cm	
Catfish	1,540-3,300	200-450 g	
NIGERIA			Bardach, et al., 1972
Common carp	25,000-30,000	30-50 mm	
PHILIPPINES			
Milkfish	1,500-6,500	-	Shang, 1976
T. nilotica	10,000-20,000	-	Bardach, et al., 1972
Common carp	50,000 (running water)	60-180 mm	
	5,000 (stagnant water)	20-50 g	
U.S.S.R.			Bardach, et al., 1972
Grass carp	500-800	Yearling	
	160-240	3-4 years	
	40,000-50,000	up to 5 g	
INDONESIA			Shang, 1972
Milkfish	4,000-6,000	-	
TAIWAN			
T. nilotica	20,000	20-30 mm	Chen, 1976
Catfish	30-60/m^2	25-35 mm	Chen, 1976
Mullet	4,000-10,000	-	Chen, 1976
Milkfish	15,000	-	Shang, 1976
THAILAND			Ling, 1977
Catfish	80-100/m^2	16 g	
	60-80/m^2	20 g	
	40-60/m^2	25 g	
JAPAN			Suzuki, 1979
Common carp	1/m^2	40-100 g	
	0.5-1/m^2	80-100 g	

Table 6

STOCKING RATE IN POLYCULTURE SYSTEMS IN SELECTED ASIAN COUNTRIES, BY SPECIES

	Common Carp	Bighead Carp	Grass Carp	Silver Carp	Grey Mullet	Java Carp	Gold-fish	Milk-fish	Others	Source
Hong Kong	1500/km^2 (2.5-3.0 cm)	975/km^2 (7.5-10 cm)	1200/km^2 (7.5-10 cm)	100/km^2 (7.5-10 cm)	17500/km^2 (2.5-3.5 cm)		875/km^2 (2.0-2.5 cm)			IPFC, 1977
Philippines	500/ha (400-500 g)	300ha/ (100-150 g)	600/ha (100-200 g)	2000/ha (200-300 g)	3000/ha (400-500 g)			1500/ha (300-	100/ha 400 g)	Bardach, 1972
Malaysia	1250/ha (5 cm)	125/ha (12-15 cm)	500/ha (12-15 cm)			2500/ha (4 cm)			625/ha	IPFC, 1977
	1250/ha ha (5 cm)	500/ha ha (12-15 cm)	125/ha ha (12-15 cm)	250/ha ha (10-12 cm)						" "
Singapore										
In nursery	— (30 g)	250/ha (40 g)	1250/ha (30 g)	250/ha (40 g)						Hora & Pillay, 1960
In fattening pond	225/ha	150/ha (2000 g)	450/ha (1500 g)	175/ha (1800 g)						

Table 5

VARIOUS COMBINATIONS OF SPECIES USED IN POLYCULTURE IN CHINA[a]

Species	Composition by no. of fish stocked, %
1. Silver carp as main species	
Silver carp	65.0
Bighead carp	10.0
Grass carp	12.0
Common carp	5.0
Wuchan fish (bream)	8.0
2. Black carp as major species	
Black carp	42.0
Grass carp	24.2
Silver carp	12.4
Bighead carp	7.4
Wuchan fish	7.4
Common carp	3.4
Golden carp	3.2
3. Grass carp as major species	
Grass carp	55.0
Silver carp	16.0
Bighead carp	10.0
Others	19.0

[a] From Tapiador, et al., 1977

In India and Pakistan, the species most commonly used for polyculture are catla (Catla catla), rohu (Labeo rohita), mrigal (Cirrhina mrigala), and calbasu (Labeo calbasu). These are shown in Table 8. Like Chinese carps, these species have suitable complementary feeding habits and behavior. The catla feeds on the surface strata; the mrigal is a bottom feeder; the rohu is a water column feeder; and the calbasu is a bottom feeder that eats mollusks. In many cases, these native species are polycultured with silver, grass, and common carps (Central Inland Fisheries Research Institute, 1978).

The essential feature of the polyculture system in Asia is the stocking in small ponds of as many as eight fish species with different feeding habits. In well-managed Asian ponds, an average annual production of 3,000 kg/ha can be achieved.

In European countries, polyculture is based largely on natural foods. It is further characterized by big fish ponds and is dominated by common carp. Common carp and tench (Tinca tinca) are polycultured in Yugoslavia; common carp and roach (Rutilus rutilus) in France; common carp with cyprinus carpio x crucian carp hybrids, gold fish, bream, and sterlet (Acipenser rughenus) in the Soviet Union (Bardach, et al., 1972).

In Africa, little information on polyculture is available. Balarin and Hatton (1979) indicated that in the past T. rendalli and S. macrochir were commonly polycultured; in more recent times, however, common carp, Helerotis niloticus, Clarias lazera, and tilapia have become important species for polyculture.

The Israeli polyculture system features the intensive management of moderate-sized ponds with fertilization and supplemental feeding. Common carp, tilapia, and/or grey mullet are usually cultured together (Table 9). In many cases, these species are polycultured with Chinese carps.

In general, the selection and combination of species for polyculture depends mainly on the compatability of the species, the availability of natural and supplementary foods, the suitability of environmental conditions, the availability of fish seed, and the demand for and price of fish.

There are two polyculture stocking practices that result in high yield, namely multi-age (or size) stocking and multi-stage stocking:

Multi-age polyculture is a practice where different fishes of different sizes are reared in the same pond from fingerling to marketable size. The practice, like the multi-size stocking in a monoculture system, requires periodic harvesting of the market-size fish and subsequent restocking with small fish. An example is provided in Table 10.

Multi-stage polyculture involves moving different species of fish through a series of ponds as they grow from fingerling to marketable size, with fish sorted in the ponds according to size. The stocking

Table 7

STOCKING COMBINATIONS IN INDONESIA POND[a]

Species	Composition under two stocking practices, % I	II
Based on Tilapia as Major Species		
Tilapia	35	40
Common carp	30	10
Tambakan	--	20
Tawes	--	15
Nilem	20	15
Gourami	15	--
Based on Tambakan and Tawes as Major Species[b]		
Tambakan	50	37.5
Tawes	10	37.5
Common carp	20	12.5
Nilem	20	12.5

[a] From Rabanal, 1968

[b] Stocking practice I (In stagnant ponds) and II (In ponds with water inflow)

Table 8

STOCKING COMBINATION PER HECTARE USED IN INDIA AND PAKISTAN[a]

Species	Stocking rate (8-13 cm) under two stocking practices	
	I	II
Catla	1,875	1,875
Rohu	3,750	3,750
Mrigal	625	625
Calbasu	—	625

[a] From Rabanal, 1968

Table 9

STOCKING COMBINATION PER HECTARE USED IN ISRAEL

Tilapia	Mullet	Common Carp	Source
1050	600 (30-70 g)	1200	Bardach, et al., 1972
5000 (2 g)	—	3000 (3.7 g)	Yashouv, 1958
1500 (50 g)	1000 (50-100 g)	2500 (200 g)	Korringa, 1976

rate decreases as fish become larger. An example is given in Table 11.

Carnivorous species are sometimes used as predators in a polyculture system, especially when cultured species reproduce in rearing ponds. For example, in tilapia culture, Clarias sp., Lates niloticus, Bagrus docmac, Micropterus salmoides, Hemichromis fasciatus, freshwater Jack Dempsey, and Cichlasoma managuense were used as predators (Balarin and Hatton, 1979; Dunseth and Bayne, 1978; Suffern, 1980). In channel catfish culture at Auburn University, largemouth bass (Micropterus salmoides) were used as predators (Swingle, 1968). In European carp culture, pike (Esox lucius) or pike-perch (Lucioperca sandra) have been used to eliminate both small carp that resulted from unexpected spawning and wild fish that entered the pond. The optimal ratio of predator to prey is determined by comparing the size of prey with

Table 10

EXAMPLE OF MULTI-STAGE POLYCULTURE IN TAIWAN

Species stocked	Stocking rate No./ha	Initial average size cm	Month of stocking
Central Taiwan			
Common Carp	1000	2.5	March-April
Grass Carp	50	7-12	March-April
Silver Carp	800	7-12	March-April
Mullet	2000	5	March-April
Mud Carp	1000	5	March-April
Bighead	100	7-12	March-April
Southern Taiwan			
Tilapia Mossambica	2000	3	February
Silver Carp	1000	10-13	February-April
Common Carp	2000	3-4	March
Mullet	2000	5	March
Mud Carp	1500	7-10	March
Bighead	400	10-13	March
Grass Carp	200	12-15	March
Walking Catfish	500	5	May
Snakehead	500	10	June

[a] From Chen, 1976

Table 11

EXAMPLE OF MULTI-STAGE POLYCULTURE IN CHINA[a]

Stage	Size of fish, g	Stocking density/ha				Rearing period, days
		Bighead	Grass Carp	Silver Carp	Mud Carp	
1	14-65	6,750	1,500			40
	14-80			3,750		
	5-20				112,500	
2	65-225	2,100	6,750			150
	80-500			600		
					37,500	
3	225-500	900	3,000			150
	500-1,000			300		
	60-270				12,750	
4	500-1,200	375	1,050			

[a] From Tapiador, et al., 1977

the size and voraciousness of the predator (Balarin and Hatton, 1979). The less voracious the predator, the higher its stocking rate needs to be. In tilapia culture, for example, 2-3% of the total stock usually consists of predators like Hemichromis fasciatus and Lates niloticus (Huet, 1972; Pruginin, 1975); when Clarias species are used as predators, though, 5-10% is the effective ratio (Meecham, 1975).

Polyculture requires a delicate stocking balance to minimize both interspecies and intraspecies competition. Interspecies competition in the carp/mullet/tilapia combination in Israel resulted in a 28% reduction in productivity of each species relative to their productivity in monoculture; however, there was a 30% increase in overall fish yields (Balarin and Hatton, 1979). Another study (Spataru and Hepher, 1977) observed that common carp stocked in high density with tilapia were preying on the tilapia fry. On the other hand, a high stocking density of tilapia will inhibit carp growth (Yashouv, 1969). Observations in Yugoslavia revealed that carp-tench competition in densely stocked ponds depressed carp production (Yashouv, 1968). These experiences in temperate-water culture may apply to tropical regions. Thus, although polyculture usually results in higher overall fish production per unit of pond, a careful choice of stocking sizes and densities is necessary.

FUTURE RESEARCH NEEDS

One of the major problems encountered in intensive aquaculture is the inadequate supply of suitable seed stock in many areas. This problem is particularly severe in those species where artificial breeding has not been successful. When the supply of seed depends on natural sources, its availability fluctuates. In many cases, there is a shortage of seed when it is needed for stock manipulation in order to increase fish production. The solution to this problem is obvious: promote the domestication process. Research in this area is needed. Meanwhile, short-range efforts should be made to improve the efficiency of fry handling and to increase the survival rate during the pond rearing period.

Current stocking rates require basic information on the quality and quantity of fish available in the pond, plus the food preferences and feeding rates of the different age groups of the species concerned. This sort of information varies from place to place and is not usually available. Research on these aspects are necessary.

The stocking information used in this section was based on various studies conducted some time ago. The systematic collection of more up-to-date stocking data for various species in different countries under different culture systems is needed.

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POND PRODUCTION SYSTEMS: FERTILIZATION PRACTICES IN WARMWATER FISH PONDS

by

Randolph Yamada

INTRODUCTION

The importance of fertilizers for enhancing pond production in modern fish culture is indisputable. However, in most tropical countries suitable fertilization practices (actual mixtures, quantities, and application schedules) have not yet been determined. The estimation of required nutrients for a pond fertilization program depends on the pond's morphology, hydrology, environs, bottom materials, and water quality; on the type of fish cultured; and on the type of fertilizer employed. In addition, fertilizer recommendations for one location may be unsuitable for another location. Nevertheless, some benefits of fertilization are shown in Table 1.

All fertilizers may be classified as either organic or inorganic. Inorganic fertilizers are nutrients in simple inorganic compound form whose primary components contain at least one of the following: nitrogen, phosphorus, and/or potassium (N-P-K). Possible secondary nutrients include calcium, magnesium, and sulfur. Trace elements include copper, zinc, boron, manganese, iron, and molybdenum (Boyd and Lichtkopper, 1979). Commercial inorganic fertilizers used in pond culture are the same as those for agricultural crops. Table 2 shows their typical composition.

Organic fertilizers are animal manures and plant wastes containing 40-50% carbon by dry weight (Woynarovich, 1975). Unlike chemical fertilizers, these materials usually have a low N-P-K content (Table 3) and must therefore be used in large quantities.

Table 1

FISH PRODUCTION INCREASE WITH FERTILIZATION VERSUS NO FERTILIZATION

Species	Increase, %	Fertilizer	Culture	Country	Source
Tilapia mossambica	440	Superphosphate	Freshwater	South Africa	van der Lingen, 1967
Tilapia sp.	370	Phosphate	Freshwater	Malaysia	Hickling, 1962
Tilapia sp., Ctenopharyngodon idella, Puntius javanicus	386-530	Phosphate	Freshwater	Malaysia	Hickling, 1962
Cyprinus carpio	172-832	Superphosphate/ ammonium sulfate	Freshwater	Israel	Hepher, 1962
Mugil cephalus	167	Phosphate	Brackish-water	United Arab Republic	El Zarka and Fahmay, 1968
Mugil cephalus, Cyprinus carpio, Chinese carp, tench	96	Superphosphate	Freshwater	Taiwan	Lin, 1968
Indian and Chinese carp polyculture	133-219	Cowdung and N-P-K	Freshwater	India	Sinha, 1979

Table 2

COMPOSITION OF SOME COMMON INORGANIC FERTILIZER MATERIALS[a]

Material	Composition, %		
	N	P_2O_5	K_2O
Ammonium nitrate	33-35	-	-
Ammonium sulfate	20-21	-	-
Calcium metaphosphate	-	62-64	-
Calcium nitrate	15.5	-	-
Ammonium phosphate	11-16	20-48	-
Muriate of potash	-	-	50-62
Potassium nitrate	13	-	44
Potassium sulfate	-	-	50
Sodium nitrate	16	-	-
Superphosphate (ordinary)	-	18-20	-
Superphosphate (double or triple)	-	32-54	-

[a] From Boyd, 1979

INORGANIC FERTILIZER

At present, there is no universally accepted method of fertilization. However, in a citation from Lahnovitch (1968), Seymour (1980) lists three schools of inorganic usage: (1) "American" - mixed nitrogen, phosphorus, and potassium fertilizer, (2) "Soviet" - nitrogen and phosphorus fertilizer, and (3) "German" - non-nitrogenous fertilizers.

Phosphorus

It has been conclusively demonstrated by German investigators that phosphorus is the most important nutrient supplement usually present in minimal supply (Wahby, 1974). Very small quantities are found in natural waters, with a concentration of only 1 ppm or 1 mg/l being considered optimal for planktonic growth (Hora and Pillay, 1962). A complex network of factors is responsible for the dynamics of the phosphorus cycle and its fixation: dilution; assimilation by macrophytes, planktonic and benthic algae, bacteria, and fungi; and adsorption to bottom deposits.

Ponds with a history of manuring have a lower rate of fixation than ponds that have not been manured (Hickling, 1962). Hepher (1958) assumed this occurs primarily because the adsorption of phosphates by mud decreases as it becomes saturated by phosphate containing fertilizers. Except in certain instances, such as those reported from Yugoslavia by Fijan (1967) where water inflow contains sufficient concentrations of phosphorus, its addition will normally be beneficial.

Nitrogen

The usefulness of nitrogen fertilizers has been questioned and they have been ruled ineffective and/or uneconomical. Although nitrogen is required by all living organisms (proteins contain about 17% nitrogen content (Woynarovich, 1975)), some investigators argue that it is unnecessary because either (1) phosphorus increases blue-green algae for nitrogen fixation, thus stimulating phytoplankton productivity (Seymour, 1980) or (2) denitrifying bacteria breakdown the added nitrogen to nullify its effect (Wahby, 1974). Furthermore, although nitrogen fertilizers have a stimulating growth effect on fish food organisms (as in the case of chironomid larvae), it may be demonstrated that equally good results can be obtained by the substitution of phosphorus and potash fertilizers, provided carbohydrate is present (Wahby, 1974). Thus in Europe, nitrogen is usually not used.

In contrast, Israel and the United States have found inorganic nitrogen compounds to be quite effective. Woynarovich (1975) attributes this contradiction to differences in stocking density. For example, temperate culture in Europe stocks 1 fish per 20 m^3 and nitrogen needs are generally met by the activities of nitrogen fixing bacteria and blue-green algae. In the more productive sub-tropical conditions in Israel, the stocking rate is typically 1 fish per 2 to 5 m^3, thus placing a critical demand on the pond's nitrogen supply. Boyd (1976) in the United States has demonstrated that Tilapia aurea production increased when nitrogen, phosphorus, and potassium fertilizers were used rather than a phosphorus, potassium control mixture (Table 4).

Hora and Pillay (1962) suggest 4:4:1 (ppm) as the best N-P-K ratio for optimal plankton production. They further recommend that since ammonia is an index of pollution (unpolluted water contains less than 0.5 ppm total dissolved ammonia), waters should have less than 2 ppm for healthy growth. However, concentrations of 4 ppm at pH 7.3 to 7.5 have not affected the growth of Tilapia, common carp, bighead carp, grass carp, silver carp, and black carp.

Potassium

Seymour (1980) considers potassium treatment to be "groundless", yet Hora and Pillay (1962) consider it an important factor in the stimulation of aquatic

Table 3

AVERAGE COMPOSITION OF SEVERAL MANURES

	Composition, %			
	Water	N	P	K
Dairy cows[b]	79	0.5	0.1	0.5
Fattening cattle[b]	78	0.7	0.2	0.5
Sheep[b]	64	1.1	0.3	1.1
Sheep[c]	-	0.7	0.3	0.3
Pig[b]	74	0.5	0.2	0.4
Pig[c]	-	0.6	0.2	0.4
Hen[b]	76	1.1	0.4	0.4
Poultry[c]	-	1.6	0.7	0.7

[a] From Schroeder, 1980

[b] Morrison (1959)

[c] FAO (1977)

flora. The general consensus is that potassium is not a limiting factor for most fish production ponds (Hickling, 1962).

ORGANIC FERTILIZERS

In most tropical countries, organic manures are far more commonly used than inorganic fertilizers. Organic manures include the following:

Green Manure

Fertilization through green manure (plant wastes) is sometimes all that is possible in depressed regions of the tropics. Animal manure, compost, and guano are generally in short supply and are reserved for fields and gardens. In ponds, rotting plant tissues often serve as a substrate for a host of aquatic invertebrates that may be a direct source of fish food.

Sewage Water

Water-borne sewage disposal has become a serious pollution problem in many parts of the world. As a partial remedy, these wastes may be recycled into fish flesh. For example, the fertility of brackish-water fishponds in Manila Bay in the Philippines may be attributed to sewage inflow from the shoreline's inhabitants. Nash and Brown (1980) and Edwards (1980) have reviewed the theory, feasibility, and practices of recycling animal, human, and agro-industrial wastes for fishpond fertilization.

Liquid Manure

Liquid manures come from the anaerobic fermentation of animal manure in bio-gas plants or from mixing fresh manure with water. Liquid manure is a powerful stimulant to phytoplankton growth producing high fish yields. The recommended application is through small, frequent dosages added in the deeper parts of the pond so that little is wasted on shoreline macrophytes (Hickling, 1962). Liquid manure from bio-gas digesters may be easily handled through pipes and canals; animal manures mixed with water require transport, handling, and bulk storage facilities, and their availability is often limited.

Animal Manure

Animal manures are the most common manures used in fish pond work. They may be applied as compost, liquid manure, or in a fresh, untreated form. In China, all three forms are utilized. The Chinese composting procedure consists of mixing cow and chicken manure with plant materials and soft mud in a composting pit and allowing it to ferment for ten days (Tapiador et al., 1977).

PATHWAY OF ORGANIC FERTILIZERS

The pathways of organic material entering the pond food web have been outlined by Tang (1970): (1) the material enters as a source of nutritive substances (e.g., carbon, phosphorus) for photosynthesis in chlorophyll bearing plants, (2) serves as an organic substrate for microorganisms which, in turn, support a zooplankton population, or (3) it may be directly consumed by fish, crustaceans, or insects.

Tang's (1970) polyculture experiment indicated that only half of the total fish growth (30 kg/ha/d) could be attributed to the consumption of natural food organisms like plankton or insects. The other half came from the direct consumption of organic materials like night soil. In another study, Noriega-Curtis (1979) observed that fish yields considerably exceeded predicted yields based upon primary production models.

He concluded that manuring not only enhances autotrophic production but also promotes fish growth through an "alternative" pathway. Other investigators concluded that this discrepancy in fish yields could be accounted for by the consumption of heterotrophic bacteria and protozoa flourishing on the organic substrate (Schroeder, 1978, 1980). If autotrophic production were solely dependent on the amount of solar energy incident to a pond, there would be predictable upper limits to fish growth. However, since heterotrophic production does not suffer from this limitation, the results of Tang (1970) and Noriega-Curtis (1979) could be explained by the presence of additional forage provided by bacteria and protozoa in the dietary regimen of pelagic and bottom feeding fishes.

POND SOILS

There are instances when the productivity of an unfertilized pond is equal to or greater than that of a fertilized one. The reason is often found in the chemical and physical properties of the soil. Pond soils, as outlined by Potter (1976):

1. Store and release plant nutrients.
2. When dried, allow bacteria to mineralize organic bottom deposits.
3. Are the substrate and source of nutrients for bottom dwelling animals and plants.
4. Regulate "water quality" (e.g., dissolved oxygen, ammonia, hydrogen sulfide).
5. Are the substrate of pond and diking material.
6. Can act as reservoir for harmful pesticides and algicides used in pond.

Soils in Brackishwater

Where the growth of benthic vegetation is considered, soils are more significant for productivity in brackishwater culture than in a freshwater pond. This is why milkfish culturalists in southeast Asia choose rich alluvial soil sites for their brackishwater ponds. The different soil types and textures are classified in Table 5.

The most suitable algal pastures for Taiwan milkfish culture appear to be silty loams, sandy loams, loam, and silt (Tang and Chen, 1967). These soils keep seepage to a minimum and form strong dikes (Chen, 1970); sandy and loamy sandy are poor soils because of their light texture and their low clay and fine silt content, which form soil colloids, the most active portion of the bottom soil. The highest fertility in Indonesia is derived from juvenile volcanic soil rich in nutrients; lowest in fertility are senile lateritic soil, rock, or sand (Djajadiredja and Poernomo, 1970). The clay loam soils of the deltaic regions in Bengal are considered very fertile (Hora and Pillay, 1962). In general, it appears that soil textures ranging from fine sandy loam to clay loam are the most suitable for brackishwater milkfish culture.

Tang and Chen (1967) state that the growth of benthic algae in brackishwater ponds is related to the nitrogen content, which is directly proportional to the amount of organic matter present. Ghosh (1975) demonstrated that there is an increased rate of nitrogen mineralization from manures with increasing salinity. In considering that the optimal ratio of N:P

Table 4

SUMMARY OF POND FERTILIZATION EXPERIMENTS USING N, P, K COMPARED WITH THOSE USING P AND K OR P ONLY FOR SEVERAL SPECIES OF FISH[a]

Fish	Nitrogen applied, kg/ha	Nitrogen source	Increase in production, %	Source
Cross-bred Tilapia	28	Calcium nitrate	10.1[b]	Hickling, 1962
Hybrid male Tilapia	28	Urea	13.1[b]	Hickling, 1962
Cyprinus carpio	90	Ammonium nitrate	11.7[b]	Swingle et al., 1965
Cyprinus carpio	90	Ammonium nitrate	13.3[b]	Swingle et al., 1965
Carassius auratus	90	Ammonium nitrate	13.9[b]	Swingle et al., 1965
Ictalurus punctatus	90	Ammonium nitrate	0.4[b]	Swingle et al., 1965
Micropterus salmoides and Lepomis macrochirus	90	Ammonium nitrate	33.6[b]	W.E. Swingle (unpublished data)
Tilapia aurea	19.9	Ammonium nitrate	31.3[c]	Boyd, 1976
Tilapia aurea	67.5	Ammonium nitrate	30.0[c]	Boyd, 1976

[a] From Boyd, 1976

[b] Increase over P fertilizer only

[c] Increase over P and fertilizer only

Table 5

SOIL TYPES AND TEXTURES

Common names	Texture	Basic soil textural class names
Sandy soil	Coarse	Sandy Loamy sands
	Moderately coarse	Sandy-loam Fine sandy loam Very fine sandy loam
		Loam
Loamy soils	Medium	Silt loam Silt Clay loam
	Moderately fine	Sandy clay loam Silty clay loam Sandy clay
Clayey soils	Fine	Silty clay Clay

[a] From Potter, 1976

for phytoplankton growth is 4:1, Djajadiredja and Poernomo (1970) found that a lack of nitrogen in certain Indonesia brackishwater pond soils was a more limiting factor that phosphate deficiency. In a Taiwan pond, available phosphorus for algal pastures appeared plentiful (42 ppm); however, the addition of organic or inorganic phosphorus, alone or in combination with nitrogen, still improved algal growth (Tang and Chen, 1967). The potassium content of sandy soils is often poor, clay soils are richer. However, this is relatively unimportant in brackishwater culture because saline waters are generally adequate in the essential elements (e.g., potassium in the form of potassium chloride) necessary for algal growth.

Soil pH can control water pH and the availability of algal nutrients. In tropical countries, the soil may often be poor in calcium but rich in ferric, alumina, or manganese compounds that render the waters acid due to the slight colloidal solution produced (Hora and Pillay, 1962; Potter, 1976). Other reasons for low pH may be the oxidation of sulfur compounds in decaying plant materials (e.g., mangrove muds) or peaty bottoms formed by plant debris that has not decomposed. The best ways to control soil acidity are (1) regular pond draining to maintain productive capacity through alternative periods of mud formation and mineralization (Hora and Pillay, 1962), and (2) liming (Potter, 1976).

Soils in Freshwater

In stagnant freshwater ponds, nutrients supplied from the pond bottom are usually more significant than those supplied from inflowing water (Hickling, 1962). However, fertile soil is generally allocated for agricultural purposes instead of freshwater culture due to its better income.

Liming

Although not strictly a fertilizer, lime can increase phytoplankton production, which in turn leads to increased fish production (see Water Quality Section). The many purposes of liming may be summarized as follows (Hora and Pillay, 1962: Woynarovich, 1975; Boyd, 1979):

1. The toxic and caustic action of liming kills bacteria, fish parasites, and their intermediate hosts.
2. In acid waters where many fish species grow poorly or do not survive, liming neutralizes undesirable iron compounds and buffers the pH to an acceptable alkaline level.
3. Liming reduces the potential of oxygen depletion by making carbon dioxide available for photosynthesis.
4. Liming may precipitate excess dissolved organic material that normally contributes to turbidity (e.g., humic stains), which interferes with light penetration for photosynthesis.
5. Liming improves soil condition and promotes the bacterial breakdown of waste material.

6. Liming assists in the release of nutrients from the soil. For example, bottom mud pH is increased, and this then increases the availability of phosphorus.

Boyd (1979) claims that a total alkalinity of 20 ppm is sufficient for the consistent production of plankton; below this level unlimed ponds experience variable responses to fertilization. There is little or no benefit to excessive liming; in fact, it may cause the precipitation of phosphorus as insoluble calcium phosphate (Hepher, 1958) and thus decrease expected fish yields. Liming to neutrality gives a linear relationship between the fish crop and the total amount of phosphate added (Djajadiredja and Poernomo, 1970). Therefore, liming needs should always be based on the total alkalinity as well as the nature of the pond soil (Table 6).

Acid Sulfate Soils

Acid sulfate soils are formed from marine and estuarine sediments that undergo extreme acidification due to the oxidation of sulfides, mainly pyrite (FeS_2). This oxidation is typically caused by drying and aeration from the tidal fluctuations of saline water or from pond draining. These soils are usually located in low coastal areas (e.g., mangroves) where topographic and hydrologic conditions are ideal for brackishwater milkfish culture. Unfortunately, these areas are also poor in productivity and are generally unsuitable for fish culture because of the following reasons (Singh, 1980):

1. Low pH (<4.0) due to the presence of sulfuric acid and iron and aluminum sulfates.

Table 6

LIMING RECOMMENDATIONS FOR AQUACULTURE PONDS[a]

	Lime requirements in hundreds of kg of calcium oxide/ha				
pH of soil	Heavy clay or loam	Loamy sand	Sand	pH of mud	Calcium carbonate required in hundreds of kg/ha
More acid than 4	40	20	12.5	Less than 4	60 - 120
4 - 4.5	30	15	12.5	4.0 - 4.5	48 - 96
4.5 - 5	25	12.5	10.0	4.5 - 5.0	36 - 72
5 - 5.5	15	10	5	5.0 - 5.5	30 - 48
5.5 - 6	10	5	2.5	5.5 - 6.0	16 - 30
6 - 6.5	5	5	0	6.0 - 6.5	14 - 16

[a] From Hora and Pillay, 1962

The types of lime available are limestone (calcium carbonate), hydrated or slaked lime (calcium hydroxide), and quicklime (calcium oxide). Limestone in the form of finely ground particles (<0.25 mm) has a high neutralizing value and is the standard by which other liming materials are measured. It is also the first choice for fish ponds. If slaked lime or quicklime is used in large quantities, the pH may be so high as to damage the fine tissues coating the gills in fish and thus cause the fish to die.

Lime can be applied on the pond bottom, added to the water at the inlet, or broadcast on the water surface. Hora and Pillay (1962) have recommended that to control the growth of parasites and to improve the pond bottom, the pond bed and not the water column should be treated. For example, slaked lime or quicklime should be applied after a pond has been drying for two weeks. When the control of gill rot disease or the precipitation of organic substances is desired, the water itself should be treated. In tropical countries, a proper fertilization program must be implemented a few weeks after liming to achieve increased pond productivity.

2. The toxic effect, especially to many plants, of excess iron and aluminum.

3. Low nutrient status (e.g., binding of phosphorus to excess iron and aluminum) and micro-nutrient deficiencies leading to low food web productivity.

4. Poor physical soil conditions.

In tropical Asia, less than 2 million of the 15 million hectares of acid sulfate soils are under cultivation.

When pH is increased through reclamation treatments, concentrations of aluminum and iron are reduced, while the availability of phosphorus is increased. Therefore, indicated pond management recommendations according to Philippine research (Singh, 1980) are as follows:

1. Tilling the pond bottom to speed up the oxidation process of pyrite, then leaching to remove acidity. The periodic drying and flushing with seawater of both the pond bottom and dikes is advised; a pH shift of

3.70 to 6.25 was recorded after this treatment.

2. Liming and proper fertilization must be followed up for the healthy growth of benthic algae. Repeated application of nitrogen and phosphorus in small quantities appears more effective than one large dosage.

Table 7 summarizes some of the results of treating acid sulfate soils in brackishwater ponds.

Apparently the Philippines is the only country currently conducting research on the reclamation of acid sulfate soils for fish culture. Although these soils can clearly be improved for fish cultivation, optimal treatments have not yet been developed and the costs involved are unknown.

APPLICATION OF FERTILIZERS

The purpose of fertilization in freshwater ponds is different in concept from that in brackishwater milkfish ponds. In freshwater culture the aim is to increase the production of planktonic algae, whereas in brackishwater culture it is to increase benthic algal growth for browsing milkfish.

Secchi Disk

An important tool to consider at this point is the secchi disk. Secchi transparency provides crude guidelines for the proper rate and amount of fertilizer treatment. Melack (1976) demonstrated that fish production is, as expected, related to primary productivity. Almazan and Boyd (1978) found that the coefficient of determination of Tilapia yields was related to primary productivity as measured by secchi disk transparency (r^2 = 0.71), chlorophyll *a* concentrations (r^2 = 0.89), actual phytoplankton counts (r^2 = 0.78), and through the light-dark bottle method (r^2 = 0.79). Since the last three methods are not practical for the fish culturalist, the secchi disk is the most suitable index of plankton abundance when plankton is the primary source of pond turbidity. Stickney (1979) recommends a depth of 30 cm to achieve and maintain proper fertilization. When a secchi disk is not available, the rule of thumb is to submerge one's arm up to the elbow and note the disappearance of the hand.

Brackishwater Inorganic Fertilization

Present large scale brackishwater milkfish culture exists only in Indonesia, the Philippines, and Taiwan. In Indonesia, some inorganic fertilizers like urea are toxic to fish; thus, ammonia carrying fertilizers are preferred. Since "kelekap" or benthic algae growth usually lasts for only 1.5 to 2 months after chemical fertilization, Djajadiredja and Poernomo (1970) have formulated these application techniques:

1. Prepare the soil by draining and tilling to make it soft and colloidal; this stimulates "kelekap" and prevents the occurrence of the snail pest Cerithidae, which is a food competitor. Biodegradable tea seed cake (200 kg/ha) or tobacco waste (100-200 kg/ha) is also effective in eradicating this snail. Cerithidae shell formation can deplete calcium supplies and has been observed in densities of 700 per square meter (Bardach et al., 1972).

2. Alter tilling and raking, Bardach et al. (1972) state lime treatments are applied to

Table 7

TOTAL FISH PRODUCTION IN PONDS GIVEN VARIOUS LEVELS OF LIME AND CHICKEN MANURE INPUTS FOLLOWING TILLING AND REPEATED LEACHINGS

Treatment	Production before treatment application[b]	Production after treatment application[c]
1. No lime; 2t/ha chicken manure	336.5	419.3
2. 4t/ha lime; 2t/ha chicken manure	478.5	555.0
3. 8t/ha lime; 2t/ha chicken manure	402.7	565.6
4. 4t/ha lime; 8t/ha chicken manure	689.0	929.8
5. 8t/ha lime; 8t/ha chicken manure	412.2	805.0

[a] From Singh, 1980

[b] Before tilling and leaching

[c] After tilling and leaching

wet, foul smelling spots to prevent anaerobic decay and production of hydrogen sulfide. The lime also kills potential predators.

3. Apply fertilizers before stocking with water level at 1-3 cm and salinity at 15-30 ppt. Several investigators favor water depths ranging from 1 to 50 cm. Regardless, the important guidelines here is adequate light penetration to the bottom and the prevention of phytoplankton blooms.

4. Wait at least one week after fertilization before stocking fish lest toxic effects occur. The best time to stock is when "kelekap" is at its maximum growth, which is about 2-3 weeks after fertilization.

These procedures were designed to maintain an adequate supply of algal pasture for 11-12 weeks, the time it takes to rear fry to the advanced fingerling stage of 8-12 cm. In the Visaya Islands, Philippines, fertilizer grades and applications recommended for "lab lab" production (benthic algal growth) are shown in Table 8. The use of inorganic fertilizers in brackishwater milkfish culture has been largely determined empirically.

Table 8

"LAB-LAB" FERTILIZATION PROGRAM

Fertilizer grade	Rate, kg/ha	Time/method of application
PRE-STOCKING:		
18-46-0	100-200	Broadcast, then admit water immediately into the pond.
18-46-0	50-100	Apply every 10-15 days up to 1 week before stocking.
POST-STOCKING:		
18-46-0	15-25	Apply 1 week after stocking. Repeat every 10-15 days interval up to harvest.

[a] From Ballesteros and Mendoza, 1976

Although chemical fertilizers are strongly promoted in Taiwan (Bardach et al., 1972), they are rarely used as replacements for organic materials in milkfish culture (Chen, 1970). Nevertheless, the recommended conditions for chemical fertilization during the rearing season when pond water levels are full are (1) clear water, (2) salinity greater than 15 ppt, and (3) a cloudless day for maximum light penetration.

Brackishwater Organic Fertilization

Manuring of nursery ponds in Indonesia is not recommended because of algal blooms that cause heavy fry mortality. In contrast, Taiwan nursery ponds are manured because blooms are considered less of a problem in the more temperate climate. Taiwan manuring may consist of rice bran placed in 22 to 30 kg bags, perhaps enriched with human waste, straw or oil cakes, and applied at 400-1000 kg/ha. The bags are then soaked in water, cut open, and the fertilizer spread around (Bardach et al., 1972).

The production ponds of Indonesia are fertilized with green manures stacked in heaps with a topping of mud to prevent drifting away at 2000 kg/ha, while in the Philippines green manure or copra slime is applied at 450-900 kg/ha (Bardach et al., 1972). In Taiwan, commercial growers continue to rely on experience and fertilize with available materials (rice bran; legume seed; soybeam or peanut cake; human, pig or chicken manures; etc.).

Organic material provides a substrate upon which benthic growth may thrive; its benefits therefore are especially realized in new ponds. However, BFAR (1976) of the Philippines concludes that inorganic fertilizers are generally more profitable than organic ones, except for new ponds and others that have low levels of rapidly decaying organic matter. The reason for this is the high cost of assembling, processing, storing, transporting, and applying organic fertilizers. This contrast with the aforementioned Taiwanese practice of rarely using chemical fertilizers is just another example of the different strategies necessitated by local pond conditions and socio-economic environments.

Freshwater Inorganic Fertilization

Hora and Pillay (1962) have recommended chemical fertilizers are best applied by raking them into a drained pond. Alternately, in ponds full of water, fertilizer may be spread from boats or by hand broadcasting. In new ponds, fertilizer should be applied 2 to 3 times per week, then later at monthly intervals. Secchi disk transparency of 45 cm is considered proper management of the phytoplankton population. Care

must be taken against over-fertilization, which can result in phytoplankton blooms with associated toxicity, oxygen depletion, and shading problems.

In Alabama, Boyd (1979) reports that large fertilizer applications over long intervals are considered wasteful because of phosphorus adsorption to muds and denitrification of nitrogen. Thus, the traditional practice is to broadcast fertilizers over shallow areas every 2 to 4 weeks. A more efficient way of preventing phosphorus from being adsorped is to place fertilizers onto underwater platforms 30 cm below the water surface where currents can distribute the nutrients as they dissolve. Two to 4 platforms per hectare of pond area are sufficient.

Freshwater Organic Fertilization

The old practice of organic manuring involves either scattering or heaping materials onto the bottom of drained ponds (Hora and Pillay, 1962). This has disadvantages when the ponds are filled, scattered manure on the pond bottom is not amenable to aerobic digestion because of the low dissolved oxygen usually present in the muds. In addition, heaps are inefficient because aerobic digestion can only occur on the outer surface, even though widespread deoxygenation is prevented. Conditions become anaerobic and may potentially produce three toxic agents: hydrogen sulfide, ammonia, and methane gas (Schroeder, 1980).

Instead, Woynarovich (1975) states that manures should be finely distributed in the water column, where abundant populations of reducing bacteria exist to decompose organic material into simpler compounds for immediate utilization by phytoplankton. The manure should be distributed over as much of the pond as possible; dispersal from a boat or by constructing a hanging-basket filled with manure and buoyed by an old car inner-tube can be pulled to and fro from the shore.

Schroeder (1978) has found that as much as 40% of the total solids in fresh cow manure can remain suspended in the water column with 50-60% of this organic matter composed of inorganic minerals. Within 1 to 2 hours, 90% of the coarse organic particles will settle to the bottom resulting in anaerobic digestion when a layer more than a few mm accumulates. Therefore, from Israeli experience, the maximum amount of manure that a pond can safely digest without undesirable anaerobic effects is about 70 to 140 kg/ha/d.

Wohfarth and Schroeder (1979) have reviewed worldwide the frequency of manuring and found that it varies from daily (through weekly, fortnightly six weekly, three monthly, and six monthly) to annually. This variation is, of course, not unexpected in view of the varying manure types, pond conditions, climates, and such social factors as labor costs, convenience, and need of disposal.

INTEGRATED AGRICULTURE-AQUACULTURE FARMING

Integrated agriculture-aquaculture farming is best exemplified by the workable patterns that have been practiced for centuries by the Chinese. Human protein needs are supplied by livestock, fowl, or fish, which are fed aquatic plants, crop wastes, and kitchen leftovers. The animal manures, in turn, serve as fertilizer for the vegetable crops and fish ponds. The water from manured ponds is also used for irrigation Unfortunately, most of these integrated systems are subsistence level operations based on empirical experience, and there is little detailed information regarding technology, economics, and yields. However, ecologically balanced animal-plantfish farming can produce yields comparable to intensive fish culture if supplementary feeds are used; the nominal cost of manures increases the potential profitability (Delmendo, 1980).

The quantity and quality of manures is determined by the animal's total live weight and the type of feed it consumes. The quality (potential biological activity) is reflected by the biochemical oxygen demand (BOD), where a higher BOD implies the rapid digestion and conversion of the organic matter by micro-organisms in the receiving waters. For example, poultry manure generally has a higher BOD than cow manure (because of poultry feed's better quality); this would require a great deal more care in application in order to prevent oxygen depletion. Schroeder (1980) has listed the general values of manures in increasing order as cow and sheep manure, followed by a grouping of pig, chicken, and duck manure.

In terms of quantity, Delmendo (1980) has estimated that the total annual tonnage of manure production per animal in China is 6.0 tons for cows, 3.0 tons for pigs, 0.8 tons for goats or sheep, and 0.025 tons for poultry. The total annual amount of organic fertilizer (derived mainly from pigs) is about 1689 million tons, which is equivalent to 8,320,000 tons of nitrogen, 5,092,000 tons of phosphorus, and 9,671,000 tons of potassium. Based upon these values and the information from Table 3, the number of animals required to supply organic nitrients to a pond can be crudely estimated.

Pig-fish farming is quite popular, with pig sties often located above or adjacent to fish ponds so that wastes may easily be washed down into the waters for fertilization. Although this practice is employed in many areas of the world, the number of pigs/unit area of pond has been standardized only in China (30-45 pigs/ha of pond) (Tapiador et al., 1977; Delmendo, 1980). Additionally, there are systems involving poultry-fish farming (Woynarovich, 1980), livestock-fish farming (Wohlfarth and Schroeder, 1979), and combination livestock-fowl-fish farming (Delmendo, 1980). Table 9 provides some examples of annual production data.

Besides animal-fish farming, there is plant-fish farming, predominatly, rice-fish systems (Coche, 1967; Huet and Tan, 1980). Two methods are generally practiced: (1) combined fish and rice culture, and (2) the rotational cropping of rice and fish (Cruz, 1980). Terrestrial crops (Beans, sweet potatoes) may be grown on paddy dikes while aquatic plants (e.g. Ipomoea, Colocasia sp.) are grown in the water. Since pesticides have become a serious problem (Koesoemadinata, 1980), Cruz (1980) has recommended adopting rotational cropping of rice and fish to reduce possible accumulation in fish tissues. Estores, Laigo, and Adordionisio (1980) report that the pesticide carbofuran is non-toxic to fish and leaves no residue.

Table 9

ANNUAL FISH PRODUCTION DATA OF WASTE UTILIZATION PROJECTS[a]

Annual production, kg/ha	Fish under culture	Manure source	Country	Reference
4,900	Carps	Fluid cowshed manure	Israel	Hepher and Schroeder, 1977
3,500	Polyculture	Ducks	Southeast Asia	Ling, 1977
4,140	Carps, catfish, largemouth bass, buffalo fish	Swine manure	USA	Buck, Baur, and Rose, 1979
2,729[b]	Silver carp, bighead carp	Sewage lagoons	USA	Henderson, 1978
3,000	Polyculture	Domestic septic tank system	Java	Hickling, 1962
3,700	Polyculture	Domestic wastewater storage reservoirs	Israel	Hickling, 1962
1,000	Carp	Fish ponds receiving sewage waters	Germany	Schaperclaus, 1961
2,000	Tilapia	Pig manure	Rhodesia	Van der Lingen, 1960
4,000	Tilapia	1,000 ducks	Rhodesia	Van der Lingen, 1960
3,000	Tilapia	Compost and farmyard manure	Madagascar	Gruber, 1966
1,300	Carp	Town sewage effluents	Poland	Wolny, 1962

[a] From Nash and Brown, 1980

[b] Area equivalents

FUTURE RESEARCH NEEDS

Optimizing fish production in a dynamic pond ecosystem by the use of fertilizers is an extremely difficult task. Since a pond's interacting biological, chemical, and physical factors are not always understood or known, the estimation of fertilizer requirements and application rates have often been determined empirically rather than scientifically.

Fertilizer problems meriting attention are currently more basic than applied. Standardized methods are needed to monitor fertilizer pathways (e.g. radioactive tracers) to quantitate the production and its utilization by the microbiological and physical community. This should help shed light on the rate of cycling and necessity of potassium and nitrogen nutrients, plus provide comparisons of the short and long-term efficiency of organic versus inorganic fertilizers.

The prospect of future energy costs behooves the further use and development of organic fertilizers in integrated agriculture-aquaculture farming systems. However, it is important to realize that because of local socio-economic-environmental conditions, recommendations in one country may be entirely unsuitable for another country.

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APPENDIX

Table 10

ADVANTAGES AND DISADVANTAGES OF ORGANIC VERSUS INORGANIC FERTILIZATION IN FISH PONDS

Item		Organic	Inorganic
1.	Quality of fertilizer based on N-P-K content	N-P-K value low	N-P-K value high
2.	Quality of N-P-K within and between various sources	Highly variable	Always consistent
3.	Serving as feed for direct consumption by fish and other fish food organisms	Yes	No
4.	Presence of growth factors for promotion of algae growth	Present	Absent
5.	Source of organic carbon for autotrophic and heterotrophic production	Yes	No
6.	Substrate for benthic algae in brackishwater milkfish culture	Yes	No
7.	Effects on physical structure of soil	Improvement	No effect
8.	Fish kills from inappropriate application	1. Oxygen depletion from plankton bloom, 2. Toxic H_2S, NH_3, CH_4, 3. Pollution	Oxygen depletion from plankton bloom
9.	Cost per unit N-P-K nutrient	Most expensive	Least expensive
10.	Cost in assembling, processing, storing, and applying	High in terms of money, labor, facilities, and general unpleasantness	Low in terms of money, labor, facilities and general unpleasantness
11.	Integrated agriculture-aquaculture farming	Low input cost using recycled wastes resulting in economically viable operation; costs minimized in (9) and (10)	Not applicable

POND PRODUCTION SYSTEMS: FEEDS AND FEEDING PRACTICES IN WARMWATER FISH PONDS

by

Randolph Yamada

INTRODUCTION

Finfish nutrition research, which is based on studies of the intake, digestion, and metabolic utilization of foods or feed, did not start producing usable results until after World War II. Fish-husbandry studies could have been patterned after agricultural work, but progress was slowed because of the adaptations necessitated by a fish's poikilothermic nature and its unique aquatic environment (Utne, 1979). Although many deficiencies still exist in the knowledge of feeds and feeding practices, the recent reviews on fish nutrition by Cowey and Sargent (1972), Halver (1972), NAS (1973, 1977), Braekken (1977), and Halver and Tiews (1979) are an impressive testimony to the endeavors in this area.

FINFISH NUTRITIONAL REQUIREMENTS

A complete fish diet must provide a suitable energy source and be in proper balance with respect to proteins, carbohydrates, lipids, and the growth factors vitamins and minerals. Precise nutritional requirements are difficult to ascertain because they change with variations in the environment, fish size/age, and reproductive condition. Until recently, a major problem for comparative studies has been the lack of standardizaion (Harris, 1978; Utne, 1979). Present knowledge of fish nutrition, primarily derived from studies of the rainbow trout (Salmo gairdneri) and channel catfish (Ictalurus punctatus), concerns requirements of the ten essential amino acids, gross protein levels, water and fat soluble vitamins, and some essential polyunsaturated fatty acids of the omega-3 and 6 series. Although very little is known about the nutritional requirements of almost all cultured fish species, it appears there is little variation in nutritional needs within the warmwater and coldwater fishes. The major difference probably concerns the essential fatty acids or lipids (Lovell, 1979a). Thus rainbow trout and channel catfish may be used as models from which to refine recommended allowances for other species.

Proteins

Proteins are a significant dietary component because of their cost and their constraints on growth. The gross protein requirements in fish are higher than in warm-blooded animals (Lovell, 1979a). Table 1 summarizes the requirements of certain fish species (Cowey, 1979); surprisingly high are the herbivores, Ctenopharyngodon idella and Brycon sp.

Lovell (1979a) states that protein levels of 30-36% will probably be adequate for most warmwater fish diets. The optimum level is influenced by several factors:

1. Fish size. Young fish have higher protein requirements than older fish.
2. Physiological function. Less protein is needed for a maintenance diet than for rapid growth.
3. Protein quality. More of a low quality protein is needed for maximum growth than high quality protein.
4. Non-protein energy in the diet. If its diet is deficient in energy, a fish will use part of its protein to meet its energy needs.
5. Feeding rate. Fish fed to less than satiation (e.g., in intensive culture) will benefit more from diets containing a high percentage of protein than fish fed at or near satiation rate.
6. Natural foods. If natural food contributes significantly to daily intake, then protein level in prepared diets may be lower.
7. Economics.

The protein requirements of euryhaline coldwater rainbow trout and coho salmon do not differ between freshwater and 20 ppt; full strength sea water has not been examined (Zeitoun et al., 1973, 1974). The requirements for euryhaline warmwater species like Tilapia sp. have never been tested in different salinities.

For optimal utilization of dietary protein, the amino acid profile of the feed should closely resemble the ten essential amino acid requirements of the fish. As shown in Table 2, real differences exist between species. Thus it is quite difficult to formulate practical diets for fish whose amino acid requirements are unknown.

Table 1

GROSS PROTEIN LEVELS FOR CERTAIN FISH SPECIES

Species	Crude protein level in diet for optimal growth, g/kg	Reference
Rainbow trout (Salmo gairdneri)	400-460	Satia, 1974 Zeitoun et al., 1976 Tiews et al.,, 1976
Carp (Cyprinus carpio)	380	Orgina and Sait, 1970
Chinook salmon (Oncorhynchus tschawytscha)	400	Delong et al., 1958
Eel (Anguilla japonica)	445	Nose and Arai, 1972
Plaice (Pleuronectes platessa)	500	Cowey et al., 1972
Gilthead bream (Chrysophrys aurata)	400	Sabaut and Luquet, 1973
Grass carp (Ctenopharyngodon idella)	410-430	Dabrowski, 1977
Brycon sp.	356	Saint Paul, 1977
Red sea bream (Chrysophrys major)	550	Yone, 1976
Yellowtail (Seriola quinqueradiata)	550	Takeda et al., 1975

When a diet is deficient in one or more amino acids, it may be possible to supplement it in the appropriate amounts. Andrews and Page (1974) substituted soybean meal fortified with methionine, cystine, or lysine (the most limiting amino acids) for menhaden meal in a channel catfish diet. The growth and feed efficiency were reduced. A similar result was obtained in young common carp when amino acid mixtures were used to replace the protein components of casein and gelatin (Aoe et al., 1970). In contrast, the chinook salmon is able to grow well with supplemental amino acids (Halver, 1957). It is too early yet to attempt to explain why certain species can use free amino acids and others cannot.

The design of practical diets with regard to proteins is a compromise. Very high protein levels will result in the deamination of amino acids and the burning-off of carbon residues for energy. Growth may subsequently be depressed by excess excretion of ammonia causing stress or gill damage in a confined, heavily stocked pond. Too little protein level will result in the accumulation of fat, producing undesirable changes in the carcass composition.

Carbohydrates

Carbohydrates comprise a broad group of substances that include sugars, starches, gums, and celluloses. The omnivorous channel catfish and common carp, as well as the herbivorous grass carp, are able to digest carbohydrates of plant origin. By contrast, carnivorous fishes do not have the capacity to handle significant quantities of complex carbohydrates in their diet. They can, however, efficiently utilize the simple carbohydrates (glucose, sucrose, lactose) as a primary energy source.

The ability to assimilate starches depends on the enzymatic activity (production of amylase) of the fish. In herbivores, amylase is widespread throughout the entire digestive tract; in carnivores, it is primarily of pancreatic origin.

Although cellulase of bacterial origin is present in the gut of the common carp (Schroeder, 1978), cellulase and galactosidase are not normally secreted by fish. This lack of galactosidase may partially explain the poor growth response of fish fed soybean meal, which contains significant amounts of galactosidic oligosaccharides, raffinose and stachyose. Since oligosaccharides undero enzymatic hydrolysis during the germination process to yield galactose and sucrose, Chow and Halver (1980) have suggested soaking soybeans for 48 hours prior to meal processing. This recommendation applies to most legume seeds, since a large portion of their carbohydrates are in the form of oligosaccharides.

Lipids

The optimal lipid requirements of almost all warmwater cultured species have not been determined. The establishment of lipid requirements is important because it costs less than proteins and because its high energy levels can spare protein. Homeothermic animal studies and the analysis of the fatty acid composition of fish oils have shown that fish lipids have a low omega-6 and high omega-3 polyunsaturated fatty acid content as compared to mammalian lipids, which have a high omega-6 and low omega-3. Mammals require omega-6 essential fatty acids (EFA) and fish require omega-3 (Cowey, 1979; Halver, 1979).

The fatty acid patterns differ between species as well as between freshwater and marine fish (Table 3) with marine fish having a higher omega-3 requirement than freshwater fish. Fatty acid patterns are also different in anadromous fish (masu salmon, Oncorhynchus masu) and catadromous fish (sweet smelt, Plecoglosus altivelis) migrating into different gradient salinities (Cowey, 1979; Halver, 1979). This is shown in Table 4. These differences may be a result of differences in the fatty acid content of their diets or of the specific dietary requirement related to physiological adaptation to the environment.

Temperature is another factor that appears to affect fatty acid composition in fish. The omega-3 requirement is greater for fish raised at a lower temperature (e.g., rainbow trout); warmwater common carp, channel catfish, and Tilapia may do better with a mixture of omega-6 and 3 fatty acids (Table 5). Generally, fish tend to utilize omega-3 over omega-6. High omega-6 diets undergo alteration of the omega-6:omega-3 ratio in favor of omega-3 fatty acids in the tissue lipids (Cowey, 1979; Halver, 1979).

Although omega-9 series can be synthesized, it appears that a critical balance of omega-3, -6, and -9 must be maintained under a particular set of environmental conditions for optimal metabolic function. Since EFA in tissues and organs are so highly influenced by diet and the specific EFA needs,

Table 2

AMINO ACID REQUIREMENTS OF CERTAIN FISH[a]

Amino acid	Amino acid requirement, g/kg dry diet					
	Chinook[b] salmon	Japanese[c] eel	Carp[c]	Channel[d] catfish	Gilthead[e] bream	Rainbow[f] trout
Arginine	24	17	16		%10.4	12
Histidine	7	8	8			
Isoleucine	9	15	9			
Leucine	16	20	13			
Lysine	20	20	22	12.3	20	
Methionine	16[g]	12[g]	12[g]		16[h]	
Phenylalanine	21[i]	22[i]	25[i]			
Threonine	9	15	15			
Trypotophan	2	4	3	2.4		
Valine	13	15	14			

[a] From Cowey, 1979

[b] Mertz, 1972

[c] Drs. S. Arai and T. Nose (private communication)

[d] Wilson et al., 1977

[e] Luquet and Sabaut, 1974

[f] Kaushik, 1977

[g] In the absence of cystine

[h] Methionine + cystine

[i] In the absence of tyrosine

Table 3

FATTY ACID PATTERNS IN FRESHWATER AND MARINE FISH[a]

	Freshwater Fish						Marine Fish						
Fatty Acid	Sheeps herd[b]	Tullibee[b]	Tullibee Flesh[c]	Maria[b]	Alewife[b]	Rain-bow[b]	Atlantic Herring[b]	Pacific Herring[b]	Atlantic Cod[b]	Chinook Salmon[c]	Mack-erel[c]	Menhadon	Deepson Smelt
14:0	2.8	4.5	5.5	3.1	6.7	2.1	5.1	7.6	3.7	2.2	4.9	8.0	1.4
16:0	16.6	13.8	17.7	13.2	14.6	11.9	10.9	18.3	12.6	17.0	28.2	28.9	17.2
16:1	17.7	21.5	7.1	16.2	14.7	8.2	12.0	8.3	9.3	4.1	5.3	7.9	11.0
18:0	3.3	2.9	3.0	2.8	1.5	4.1	1.2	2.2	2.3	3.2	3.9	4.0	3.7
18:1	26.1	25.2	18.1	29.1	18.2	19.8	12.6	16.9	22.7	21.4	19.3	13.4	31.4
18:2ω6	4.3	1.9	4.3	2.2	3.7	4.6	0.7	1.6	1.5	2.0	1.1	1.1	0.2
18:3ω3	3.6	2.6	3.4	1.9	3.6	5.2	0.3	0.6	0.6	1.0	1.3	0.9	
18:4ω3	0.9	1.5	1.8	1.3	2.9	1.5	1.5	2.8	0.6	2.0	3.4	1.9	
20:1	2.4	1.3	1.2	1.2	1.6	3.0	16.1	9.4	7.5	5.4	3.1	0.9	4.8
20:4ω5	2.6	1.7	3.4	2.4	2.4	2.2	0.4	0.4	1.4	0.9	3.9	1.2	2.5
20:4ω3	0.7	0.8		1.1	1.5		0.4		0.6				
20:5ω3	4.7	6.2	5.9	5.5	8.2	5.0	7.4	8.6	12.9	6.7	7.1	10.2	3.6
22:1	0.3	0.3	2.8	0.3	0.4	1.3	19.8	11.6	6.2	9.4	2.8	1.7	2.5
22:5ω6	0.4	0.5		0.9	1.3	0.6	0.4		0.3	0.6		0.7	2.5
22:5ω3	2.0	1.8	3.3	2.4	1.5	2.6	1.1	1.3	1.7	2.3	1.2	1.6	0.3
2222:6ω3	2.0	3.8	13.3	7.8	6.0	19.0	3.9	7.6	12.7	16.1	10.8	12.8	15.0
ε sat	25.5	23.2	27.2	20.6	24.9	18.1	17.8	20.1	19.7	22.4	37.0	40.9	22.3
ε mono	49.1	49.6	33.6	48.7	36.5	32.3	61.5	46.2	47.1	40.3	30.5	23.9	49.7
ε ω5	8.5	5.4	9.9	6.7	9.4	8.0	1.9	2.0	3.7	4.2	5.0	3.0	5.7
ε ω3	14.3	17.0	31.1	20.4	24.2	33.3	14.6	20.9	29.1	28.1	23.8	27.4	19.9
ω6/ω3	0.59	0.32	0.32	0.33	0.39	0.24	0.13	0.10	0.13	0.15	0.21	0.11	0.28
Mean ω6/ω3		0.37 ± 0.12						0.16 ± 0.06					

[a] From Castell, 1979

[b] Ackman, 1967, whole fish lipid

[c] Grager et al, 1964, flesh lipid

[d] Lewis, 1967, flesh lipid

Table 4

CHANGES IN FATTY ACID COMPOSITION IN MIGRATING FISH[a]

Fatty Acid	Sweet smelt[b]				Masu salmon[c]			
	April Marine		May Freshwater		May Freshwater		June Marine	
	TG	PL	TG	PL	TG	PL	TG	PL
14:0	8.0	2.3	10.0	8.6	5.2	1.9	5.7	2.2
16:0	21.6	22.6	18.7	31.8	19.9	30.1	20.0	27.0
16:1	10.0	3.2	17.0	11.3	11.6	4.5	8.7	2.9
18:0	2.8	4.4	2.9	8.1	4.6	4.0	3.9	5.9
18:1	12.8	9.6	11.5	18.9	23.3	11.2	21.7	13.5
18:2	2.8	0.9	4.3	1.5	3.9	1.3	1.7	0.6
18:3ω3	3.0	0.0	5.1	0.9	3.0	1.2	1.3	0.5
18:4ω3	5.1	1.0	4.3	0.7	1.4	0.4	2.3	0.5
20:1	1.1	0.5	--	--	3.0	0.6	6.7	1.8
20:4ω6	1.4	1.3	1.5	1.3	1.0	2.3	0.6	0.9
20:4ω3	1.9	0.7	1.8	0.7	1.5	1.3	1.2	0.9
20:5ω3	8.2	10.9	6.3	1.4	4.2	8.5	7.0	7.6
22:1	--	--	--	--	1.9	--	4.2	0.5
22:5ω6	--	--	1.1	--	--	--	--	--
22:5ω3	1.4	1.5	1.2	1.1	1.8	2.1	2.4	2.2
22:6ω3	12.1	34.5	5.2	2.1	6.7	26.3	9.0	31.6
ε sat	34.9	31.8	35.1	53.8	31.9	37.5	31.0	36.0
ε mono	27.4	16.1	32.0	35.9	43.0	18.6	43.1	19.2
ε ω 6	4.4	2.2	7.2	3.2	5.7	4.0	2.3	1.5
ε ω 3	31.7	49.4	23.9	6.9	18.6	39.8	23.2	43.3
ω6/ω3	0.14	0.04	0.30	0.46	0.31	0.10	0.10	0.03

[a] From Castell, 1979
[b] Ota and Takagi, 1977, flesh lipids
[c] Ota, 1976, fresh lipids

the ovaries and eggs of a fish probably best represent the EFA requirements of the species.

Excessive dietary lipid may result in nutritional diseases like fatty liver or cause large fat deposition in the muscle and viscera, thus producing off-flavors, spoiling the quality of the fish, and reducing its dress-out weight percentage.

The addition of omega-3 polyunsaturated fatty acids in fish diets creates storage problems. Lipids are very labile to oxidation; the nutritional level of proteins and vitamins may be reduced and the oxidative products may be lethal. The addition of alpha-tocopherol acetate or vitamin E provides a sparing anti-oxidant effect on the lipids. A further reduction in lipid oxidation may be achieved by storing finished feed in air-tight containers at low temperatures with minimum exposure to UV radiation.

Growth Factors

Vitamins and Minerals The vitamin requirements, which play a major role in fish physiology, are related to species, size, environmental conditions, and the amount of physiological stress encountered. Most fish have requirements for 11 water-soluble vitamins and at least 3 of the 4 fat-soluble vitamins (Halver, 1979). These requirements are summarized in Table 6, which gives the vitamin requirements for growth in certain fish species.

Minerals have a great diversity of uses within the fish body, yet they have been largely neglected in studies of fish nutrition because they are difficult to quantify. Fish have the ability to absorb ions not only from their diet but also by ion exchange across the gills and skin (Lall, 1979). The trace elements, which are not yet clearly defined, should be incorporated into artificial diets used in intensive culture conditions. Since the exact trace requirements are not known, Chow and Schell (1979) recommend arbitrary levels that are based upon land animal requirements. Table 7 summarizes information on the mineral requirements of fish.

FEED EFFICIENCY

A discussion of the ability of fish to efficiently convert food into edible flesh requires a brief statement on nutritional bioenergetics.

Bioenergetics

Bioenergetics is concerned with the energy transformations in living organisms. It has recently been reviewed by Webb (1978), Fischer (1979),

Table 5

TEMPERATURE EFFECT UPON FATTY ACID COMPOSITION[a]

Fatty acid	Mosquito fish[b]		Guppies[b]		Guppies[c]		Goldfish[d] intestine		Catfish Liver[e] Beef tallow		Menhaden oil	
	14–15C	26–27C	14–15C	26–27C	17C	24C	3C	32C	20C	33C	20C	33C
14:0	1.3	1.6	3.9	3.7	1.5	0.9			0.6	1.1	0.8	1.3
16:0	14.7	16.0	19.2	22.5	22.9	36.0	15.6	17.3	16.4	18.9	17.4	18.1
16:1	20.0	19.8	10.1	14.1	15.9	8.9	2.2	0.9	4.2	4.6	2.1	3.0
18:0	5.4	6.5	10.4	7.7	8.2	9.8	12.4	19.5	9.1	6.7	10.6	10.7
18:1	31.8	30.8	26.6	25.7	18.3	15.0	7.7	11.9	45.4	56.1	26.5	40.0
18:2ω6	7.3	7.9	15.0	8.0	Tr	Tr	14.3	21.1	1.7	1.7	2.2	2.0
18:3ω3	Tr	Tr	0.1	1.7	1.4	0.8	—	—	2.4	1.6	1.0	1.9
18:4ω3	0.4	1.0	0.8	1.3	—	—	—	—	—	—	—	—
20:1	5.0	5.1	2.5	3.6	—	—	2.2	1.2	—	—	—	—
20:2	—	—	—	—	—	—	1.6	4.2	—	—	—	—
20:3	—	—	—	—	—	—	3.9	6.4	6.5	2.6	1.2	0.4
20:4ω6	4.0	4.5	1.5	2.7	2.0	2.0	13.7	6.0	3.8	0.9	2.6	1.1
20:5ω3	1.2	1.2	0.5	0.7	4.8	4.6	—	—	1.4	0.9	8.5	5.5
22:1	—	—	—	—	—	—	—	—	—	—	—	—
22:4ω6	0.4	—	0.3	—	1.3	1.0	—	—	0.6	0.7	0.4	0.5
22:5ω6	—	—	—	—	—	—	—	—	+	+	+	+
22:5ω3	2.1	1.4	1.5	0.6	6.1	7.3	3.0	2.9	1.3	1.7	3.6	2.8
22:6ω3	5.9	3.6	5.1	4.0	16.5	11.5	18.2	5.0	2.8	0.6	22.0	10.4
ε Sat.	21.4	24.1	33.5	33.9	32.6	46.7	28.0	36.8	26.1	26.7	28.8	30.1
ε Mono	56.8	55.7	39.2	43.4	34.2	23.9	12.1	14.0	—	—	—	—
ε ω 6	11.3	12.4	16.5	10.7	3.2	3.0	28.0	27.1	7.1	4.5	5.0	4.1
ε ω 3	9.6	7.2	8.0	8.3	28.8	24.2	21.2	8.4	8.3	4.5	35.9	21.2
ω5/ω3	1.18	1.72	2.06	1.30	0.11	0.12	1.32	3.23	0.86	1.00	0.14	0.19

a From Castell, 1979
b Knipprath and Meed, 1965 fed trout pellets
c Kayana et al., 1963 fed Artemia salina
d Kemp and Smith, 1970
e Stickney and Andrews, 1971 fed casein based artificial diet with 10% lipid supplement as noted.

Braataen (1979), and Smith (1980). Many energy budget models have been proposed for different fish species, with the general energy budget equation expressed as follows (Braaten, 1979):

$$C = F + U + \Delta B + R$$

where

$$R = R_s + R_d + R_a$$

C = energy value of food consumed
F = energy value of feces
U = energy value of materials excreted in the urine or through the gills or skin

Table 6

VITAMIN REQUIREMENTS FOR FISH[a,b]

Vitamin, (mg/kg) dry diet	Carp	Channel catfish	Eel	Sea breax	Turbot	Yellow-tail
Thiamin	2-3	1-3	2-5	R[c]	2-4	R
Riboflavin	7-10	R	R	R	R	R
Pyridoxine	5-10	R	R	2-5	R	R
Pantothenate	30-40	25-50	R	R	R	R
Niacin	30-50	R		R	R	R
Folacin		R	R		R	
Cyanocobalamin		R		R		
myo-Inositol	200-300	R		300-500		
Choline	500-600	R		R	R	
Biotin	1-15	R	R		R	
Ascorbate	30-50	30-50		R		R
Vitamin A	1000-2000 IU	R				R
Vitamin E[d]	80-100	R				R
Vitamin K	R	R				R

	Rainbow trout	Brook trout	Brown trout	Atlantic salmon	Chinook salmon	Coho salmon
Thiamin	10-12	10-12	10-12	10-15	10-15	10-15
Riboflavin	20-30	20-30	20-30	5-10	20-25	20-25
Pyridoxine	10-15	10-15	10-15	10-15	15-20	15-20
Pantothenate	40-50	40-50	40-50	R[c]	40-50	40-50
Niacin	120-150	120-150	120-150	R	150-200	150-200
Folacin	6-10	6-10	6-10	5-10	6-10	6-10
Cyanocobalamin	R	R	R	R	0.015-0.02	0.015-0.02
myo-Inositol	200-300	R	R	R	300-400	300-400
Choline	R	R	R	R	600-800	600-800
Biotin	1-1.5	1-1.5	1.5-2		1-1.5	1-1.5
Ascorbate	100-150	R	R	R	1-1.5	1-1.5
Vitamin A	2000-2500 IU	R	R		R	R
Vitamin E[d]	R	R	R		40-50	R
Vitamin K	R	R	R		R	R

[a] From Halver, 1979

[b] Fish fed at reference temperature with diets at about protein requirement.

[c] R - required.

[d] Requirement directly affected by amount and type of unsaturated fat fed.

Table 7

MINERAL REQUIREMENTS OF FISH[a]

Mineral element	Principal metabolic activities	Deficiency symptoms	Requirement, g/kg dry diet
Calcium	Bone and cartilage formation; blood clotting; muscle contraction	Not defined	5
Phosphorus	Bone formation; high energy phosphate esters; other organo-phosphorus compounds	Lordosis, poor growth	7
Magnesium	Enzyme co-factor extensively involved in the metabolism of fats, carbohydrates and proteins	Loss of appetite, poor growth, tetany	0.5
Sodium	Primary monovalent cation of intercellular fluid; involved in nerve action and osmoregulation	Not defined	1-3
Sulphur	Integral part of sulphur amino acids and collagen; involved in detoxification of aromatic compounds	Not defined	3-5
Chlorine	Primary monovalent anion in cellular fluids; component of digestive juice (HCl); acid-base balance	Not defined	1-5
Iron	Essential constituent of haeme in haemoglobin, cytochromes, peroxidases, etc.	Microcytic, homochronic anaemia	0.05-0.10
Copper	Component of haeme in haemocyanin (of cephalopods); co-factor in tyrosinase and ascorbic acid oxidase	Not defined	1-4
Manganese	Co-factor for arginase and certain other metabolic enzymes; involved in bone formation and erythrocyte regeneration	Not defined	0.02-0.05
Cobalt	Metal component of cyanocobalamin (B_{12}). Prevents anaemia; involved in C_1 and C_3 metabolism	Not defined	0.005-0.01
Zinc	Essential for insulin structure and function; co-factor of carbonic anhydrase	Not defined	0.03-0.10
Iodine	Constituent of thyroxine; regulates oxygen use	Thyroid hyperplasia (goiter)	0.10-0.30
Molybdenum	Co-factor of xanthine, oxidase, hydrogenases and reductases	Not defined	(trace)
Chromium	Involved in collagen formation and regulation of the rate of glucose metabolism	Not defined	(trace)
Fluorine	Component of bone appatite	Not defined	(trace)

[a] From Chow and Schell, 1979

Table 8

NUTRITIONAL COMPOSITION OF SOME FEED MATERIALS[a]

Fodder	Average composition, %							Digestible nutrients, %				Mineral comp., %			
	Dry matter	Crude protein	Oil (ether extract)	Carbohydrate (nitrogen free extractives)	Crude fibre	Ash	True protein	Dig. crude protein	Dig. oil	Dig. fibre	Dig. carbohydrate (nitrogen free extractives)	C_aO	P_2O_s	K_2O	Author
Green fodders															
Guinea grass, cut at 3-week intervals	23.0	2.9	0.2	10.3	6.6	3.0	—	2.5	0.1	5.3	8.9	0.06	0.07	—	Teik[170]
Roadside grasses (Malaya)	23.0	2.4	0.5	12.5	6.0	1.6	—	1.3	0.2	3.7	7.8	0.28	0.09	—	ditto
Lallang grass (Imperata arundinacea), cut at intervals of 4 weeks (Malaya)	36.4	4.3	0.7	17.1	11.7	2.6	—	2.4	0.3	7.1	10.6	0.07	0.16	—	ditto
Kudzu (Pueraria phseoloides), leaves and stems (Malaya)	19.1	3.8	0.4	7.9	5.5	1.5	—	2.9	0.2	3.3	6.5	0.19	0.08	—	ditto
Pueraria javanlca (Congo)	20.0	4.4	0.4	6.5	7.2	1.5	—	—	—	—	—	—	—	—	Couvreur et Maes[171] recalculated
Centrosema pubescens, leaves and stems (Malaya)	24.3	5.4	0.6	8.5	7.5	2.3	—	4.1	0.4	4.5	6.9	0.19	0.11	—	Teik
Water-Kangkong (Ipomaea reptans), leaves and stems (Malaya)	7.5	2.1	0.2	2.9	0.9	1.4	—	1.8	0.1	0.8	2.8	0.13	0.17	—	ditto
Sweet potato (Ipomaea batata leaves and stems (Congo)	13.0	1.6	0.4	6.8	2.3	1.6	—	—	—	—	—	0.21	0.10	—	Couvreur et Maes[171] (recalculated)
Sweet potato (Ipomaea batata (Malaya), Vines	13.3	2.5	0.3	6.5	2.5	1.5	—	1.9	0.2	1.5	5.3	0.14	0.09	—	Teik[170]

Continued next page

Fodder	Average composition, %							Digestible nutrients, %				Mineral comp., %			
	Dry matter	Crude protein	Oil (ether extract)	Carbohydrate (nitrogen free extractives)	Crude fibre	Ash	True protein	Dig. crude protein	Dig. oil	Dig. fibre	Dig. carbohydrate (nitrogen free extractives)	C_aO	P_2O_5	K_2O	Author
Manioc, tapioca (Manihot utilitissima), leaves and stems (Malaya)	23.1	4.5	1.2	11.8	3.9	1.7	—	2.7	0.8	2.1	7.7	0.28	0.19	—	ditto
Manioc, tapioca (Manihot utilitissima), leaves and stems (Congo). First leaf	27.2	9.4	0.8	6.2	9.3	1.5	—	—	—	—	—	0.26	0.21	—	Couvreur et Maes[171] (recalculated)
ditto (Congo). First six leaves	27.3	8.8	0.9	6.2	9.8	1.7	—	—	—	—	—	0.32	0.28	—	ditto
ditto. Old leaves	27.6	6.8	1.5	7.5	9.9	2.0	—	—	—	—	—	0.36	0.31	—	ditto
Coco-yam (Colocasia sp.), leaves (Malaya)	12.1	2.3	0.7	6.1	1.4	1.6	—	1.5	0.3	0.8	4.6	0.21	0.07	—	Teik[170]
Queensland Lucerne (Stylosanthes) (Malaya)	24.0	4.0	0.4	9.6	7.6	2.4	—	2.3	0.1	1.6	4.5	0.52	0.31	—	ditto
Velvet bean (Mucuna utilis), leaves and stems (Malaya)	16.6	5.8	0.5	6.4	2.4	1.5	—	4.4	0.3	1.4	5.2	0.21	0.16	—	ditto
Velvet bean (Mucuna utilis) in flower (Congo)	18.0	3.4	0.5	7.2	5.8	1.1	—	—	—	—	—	0.21	0.12	—	Couvreur et Maes[171] (recalculated)
Maize (Zea mays), leaves and immature cobs (Malaya)	20.0	3.0	0.6	12.2	2.3	1.7	—	1.8	0.4	1.4	7.9	0.08	0.15	—	Teik[170]
Maize (Zea mays), leaves (Europe)	19.4	1.7	0.5	10.4	5.6	1.2	1.3	1.0	0.3	3.1	6.7	—	—	—	Evans[73]
Pistla stratioias (Malaya)	7.1	1.4	0.3	2.6	0.9	1.9	—	1.2	0.2	0.8	2.5	0.20	0.06	—	Teik[170]
Water Hyacinth (Eichhornia crassipes) (Malaya)	5.9	1.0	0.1	2.4	1.2	1.2	—	0.7	0.1	0.6	2.2	0.19	0.05	—	ditto

Myriophyllum (Minnesota)	13.6	2.4	0.2	6.8	1.8	2.5	—								Gortner[179] (recal-culated)
Potamogation (Minnesota)	22.7	3.3	0.4	10.5	4.9	3.7	—								ditto
Ceratophyllam (Minnesota)	14.3	2.4	0.3	6.0	2.0	3.2	—								ditto
Seeds and roots															
Maize (Zea mays), (Malaya)	86.2	8.8	4.3	70.4	1.3	1.4	—	7.0	2.6	0.5	64.8	0.02	1.00	—	Teik[170]
Maize (Europe)	87.0	9.9	4.4	69.2	2.2	1.3	9.4	7.9	2.7	0.8	63.7	0.02	0.82	0.40	Evans[73]
Maize flaked (Europe)	89.0	9.8	4.3	72.5	1.5	0.9	9.4	9.4	2.0	0.5	70.4		0.60	0.25	ditto
Oats (Europe)	87.0	10.4	4.8	58.4	10.3	3.1	9.5	8.0	4.0	2.6	44.9	0.14	0.81	0.55	ditto
Barley (Europe)	85.0	9.0	1.5	67.4	4.5	2.6	8.5	6.8	1.2	2.5	61.7	0.07	0.84	0.57	ditto
Rye (Europe)	87.0	11.6	1.7	69.8	1.9	2.0	10.7	9.6	1.1	1.0	64.2	—	—	—	ditto
Wheat (Europe)	87.0	12.2	1.9	69.3	1.9	1.7	11.0	10.3	1.2	0.9	63.8	0.05	0.55	0.60	ditto
Rice, hulled (Malaya)	88.7	8.4	2.1	76.7	0.7	0.8	—	7.3	1.1	0.3	74.4	0.01	0.65	—	Teik[170]
Broken rice (white), (Malaya)	88.6	7.5	0.5	79.9	0.2	0.5	—	6.5	0.3	0.1	77.5	0.02	0.14	—	ditto
Lupin, sweet (yellow), (Europe)	87.0	41.8	5.5	24.8	10.4	4.5	38.7	37.8	4.6	9.5	18.8	0.29	1.24	1.43	Evans[73]
Groundnuts (Arachia hypogora)	94.0	26.8	44.9	17.5	2.6	2.2	24.9	24.1	40.3	0.2	14.7	—	—	—	ditto
ditto (decorticated), (Malaya)	92.7	30.8	44.3	13.6	1.6	2.4	—	27.7	39.9	0.1	11.4	0.10	0.90	—	Teik[170]
Cottonseed (Bombay)	91.0	17.8	19.3	29.7	19.9	4.3	16.5	12.2	16.7	15.1	14.9	—	—	—	Evans[73]
ditto (Egyptian)	91.0	19.6	23.8	21.4	21.2	5.0	18.2	13.4	20.6	16.1	10.7	—	—	—	ditto
Soybean (Glyeine)	90.0	33.2	17.5	30.5	4.1	4.7	29.9	29.5	15.8	1.7	20.8	—	—	—	ditto
ditto (Malaya)	88.5	38.5	16.4	24.1	4.9	4.6	—	34.3	14.4	1.8	16.1	0.37	1.30	—	Teik[170]
Acorns, fresh	50.0	3.3	2.4	36.3	6.8	1.2	2.8	2.7	1.9	4.1	32.6	—	—	—	Evans[73]
Potatoes	23.8	2.1	0.1	19.7	0.9	1.0	1.6	1.1	—	—	17.7	0.03	0.18	0.60	ditto

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Fodder	Average composition, %							Digestible nutrients, %				Mineral comp., %			
	Dry matter	Crude protein	Oil (ether extract)	Carbohydrate (nitrogen free extractives)	Crude fibre	Ash	True protein	Dig. crude protein	Dig. oil	Dig. fibre	Dig. carbohydrate (nitrogen free extractives)	C_aO	P_2O_s	K_2O	Author
Sweet potatoes (Ipomoea batala), tubers (Malaya)	25.4	1.3	0.1	22.7	0.8	0.5	—	0.7	0.1	0.3	20.4	0.03	0.07	—	Teik[170]
Manioc, tapioca (Manihot utilitissima, whole roots, fresh (Malaya)	37.6	0.4	0.2	35.5	0.8	0.7	—	0.1	0.1	0.6	19.9	0.03	0.05	—	ditto
Manioc refuse, fresh (Malaya)	20.0	0.4	0.1	17.6	1.6	0.3	—	0.1	0.1	1.3	9.9	0.04	0.05	—	ditto
Oil cakes															
Coconut cake, single pressing (Malaya)	83.7	17.3	16.3	42.8	7.5	4.8	—	13.5	16.0	4.8	35.5	0.06	1.30	—	ditto
Coconut cake	90.0	21.2	7.3	44.2	11.4	5.9	19.7	16.6	7.1	7.2	36.6	0.16	1.27	2.41	Evans[73]
Groundnut cake (decorticated) (Malaya)	92.2	47.9	10.9	25.0	3.6	4.8	—	43.1	9.9	1.3	21.3	0.10	1.22	—	Teik[170]
Groundnut cake (Congo)	87.9	44.4	7.2	22.9	9.0	4.6	—	—	—	—	—	—	—	—	Couvreur et Maes[171] (recalculated)
Groundnut cake (decorticated)	90.0	4.54	6.0	26.4	6.5	5.7	42.5	40.5	5.4	0.5	22.4	0.20	1.30	1.30	Evans[73]
Cotton cake (decorticated)	90.0	41.1	3.0	26.4	7.8	6.7	39.6	35.3	7.5	2.2	17.7	0.30* (uncorticated)	2.50*	1.50*	ditto
Palm kernal cake	89.0	19.2	6.0	46.5	13.4	3.9	18.1	17.5	5.3	5.1	39.4	0.30	1.10	0.50	ditto
ditto double pressing (Malaya)	89.0	13.1	10.0	54.9	7.7	3.3	—	10.0	9.0	3.0	45.6	0.18	1.14	—	Teik[170]
Palm cake (Congo)	87.7	27.1	14.3	32.0	10.1	3.6	—	—	—	—	—	—	—	—	Couvreur et Maes[171] (recalculated)

Miscellaneous and animal foods															
Urban pig swill (summer)	25.0	4.1	3.1	12.4	2.4	3.0	—	2.7	2.5	0.9	10.9	0.23	0.18	—	Evans[73]
Mill swinepigs (Congo)	88.2	12.3	2.4	42.1	22.4	8.9	—	—	—	—	—	—	—	—	Couvreur Maes[171] (recal-culated)
Soybean refuse, fresh (Malaya)	14.1	5.5	0.7	5.8	1.6	0.5	—	4.7	0.6	1.1	5.7	0.12	0.11	—	Teik[170]
Brewers grains, dried	89.7	18.3	6.4	45.9	15.2	3.9	17.4	13.0	5.6	7.3	27.6	0.40	1.60	0.20	Evans[73]
Padibran, coarse (Malaya)	90.5	6.2	2.7	37.8	33.1	10.7	—	4.3	2.2	8.6	28.0	0.10	0.90	—	Teik[170]
Padibran, fine (Malaya)	89.2	11.4	6.8	45.4	14.1	11.5	—	7.9	5.6	3.7	33.6	0.09	0.83	—	ditto
Fresh fish (Malaya)	28.0	14.2	1.5	—	—	10.7	—	11.5	1.5	—	—	4.18	1.79	—	ditto
Fish meal, white	87.0	61.0	3.5	1.5	—	21.0	37.0	55.0	3.3	—	1.2	10.0	9.0	1.2	Evans[73]
Blood meal	86.0	81.0	0.8	1.5	—	2.7	71.9	72.7	0.8	—	—	0.05	0.22	0.31	ditto
Silkworm pupse, fresh	35.4	19.1	12.8	2.3	—	1.2	—	—	—	—	—	—	—	—	ditto
ditto dried	90.0	35.9	24.5	6.6	—	1.9	—	—	—	—	—	—	—	—	ditto
ditto dried and defatted	91.1	75.4	1.8	8.4	—	5.6	—	—	—	—	—	—	—	—	ditto

[a] From Hickling, 1962

ΔB = total change in energy value of materials of body (growth)

R = total energy of metabolism: this can be subdivided as follows: $R_s + R_d + R_a$

R_s = energy equivalent to that released in the course of metabolism of unfed and resting fish (standard metabolism)

R_d = additional energy released in the course of digestion, assimilation and storage of minerals consumed (including SDA).

R_a = additional energy released in the course of swimming and other activity.

The ability to isolate individual components in the above equation has improved in the past ten years due to better experimental techiques. Braaten (1979) has reviewed the current methodologies.

The metabolic energy requirements of fish are less than those of mammals and birds for the following reasons (Lovell, 1979a,b; Smith, 1980):

1. Poikilothermic fish do not have to expend energy to maintain a constant body temperature.

2. Fish exert relatively little muscle activity or energy to maintain position in the water compared to land animals.

3. The excretion of nitrogen waste requires less energy in fish than in homeothermic animals.

Thus fish can synthesize more protein per calorie of energy consumed than poultry or livestock. Lovell (1979b) concludes the primary advantage of fish over other domesticated animals is the lower energy cost of protein gain rather than any superior food conversion efficiency.

Approximately 60 percent of energy in fish feeds is utilized for maintenance; the remaining 40 percent is used for growth (Hepher, 1975). It is important that the correct quality and quantity of energy sources (proteins, carbohydrates, and lipids) be incorporated into diets. The maintenance ration must have priority over the growth ration in order to ensure normal basal metabolism. Consequently, Hickling (1962) recommends that fish should be subject to as little disturbance as possible to avoid reduced growth rates. Trout culture is the exception; here the need for water currents for oxygenation outweighs the weight gain factor.

Protein is used very efficiently by fish, having metabolizable energy = 4.5 kcal/g (Smith, 1980), but it is the most expensive energy source in manufactured diets and should be kept to the minimum consistent with good growth and food conversion. Some natural foods contain a greater percentage of protein than is required for growth (Hepher, 1975). Much of this excess protein is wasted. On the other hand, insufficient protein retards growth. Fish eat to satisfy their metabolic requirements and cease feeding when their caloric needs are met (Lovell, 1979a). Consequently, if their diet contains too much energy in relation to protein, they will not meet their daily protein needs for optimum growth, even if they feed to satiation. Furthermore, there will be a tendency for increased fattiness in the fish (Nose, 1979).

Carbohydrates are the cheapest source of energy. Their value depends on the type of carbohydrate and the processing to which it has been subjected. The metabolic energy values for fish range from near zero for cellulose to about 3.8 kcal/g for easily digested sugars (Smith, 1980). It appears that warmwater fishes are better able to use starches than the coldwater fishes (Lovell, 1979a).

Fats are the long-term storage products for energy metabolism. They are generally well digested and utilized by fish, having a metabolizable energy value of about 8.5 kcal/g (Smith, 1980).

Food Conversion Ratio

In general, fish can convert food into body tissue more efficiently than can farm animals. As previously mentioned, Lovell (1979a,c) attributes this superiority to the ability of fish to better assimilate diets with higher percentages of protein because of their lower energy requirements.

Feed efficiency has traditionally been given special attention and, according to the literature, is usually expressed in one of two ways (Utne, 1979):

Food Converstion Ratio = (Feed Intake/Weight Gain)

OR

Conversion Efficiency = (Weight Gain/Feed Intake) x 100

For consistency in discussion, the term food conversion ratio (FCR) will be used throughout the text.

The FCR assumed that all food has been consumed and that the same units of measurement are used (Reay, 1979). These ratios are often expressed in terms of dry weight of food:wet weight of fish, which is why 1:1 ratios are frequently reported. However, not all the food may be consumed (at least by the targeted fish population), nor is the consumption of natural food from the pond included. Consequently, Hepher (1975) uses the term "apparent food conversion ratio."

In addition to the FCR, Swingle (1968) expressed pond conversion values (S) as:

S = Feed Added in Pond/Net Fish Production from Pond

It is again assumed that most of the feed is consumed by fish. S values for channel catfish have ranged from 1.2 to 2.0 (Boyd, 1979).

In conventional fish culture, Hepher (1975) and Schroeder (1980) state that supplemental feed in the form of grains (e.g., sorgham) to produce 5-10 tons of common carp/ha/year should have a FCR of 2.5 to 3.5. For fish meal enriched pellets containing 25% protein, the FCR ranges from 2.0 to 2.5. In polyculture, where natural food is utilized more

efficiently, the FCR of supplemental feeds should be lower. For manured polycultured ponds in Israel, common carp, silver carp, and Tilapia hybrids were grown in liquid cow wastes and produced a manure conversion ratio of about 6.6 for kg dry manure/kg wet fish weight and about 4.5 for kg organic matter in manure/kg wet fish weight (Noriega-Curtis, 1979). Interestingly, Schroeder (1973) found that the most important factor affecting FCR in manured ponds was the abundance of natural food in the form of heterotrophs instead of autotrophs.

The nutritional composition and the FCR of different feed materials are listed in Tables 8 and 9 respectively. These tables have often been presented in other publications (e.g., Ling, 1967) and provide excellent relative comparisons.

According to Hickling (1962) and Hora and Pillay (1962) the factors affecting FCR are:

Physical environment:

1. Increased water temperature increases food consumption.
2. Decreased dissolved oxygen reduces food consumption (e.g., Tilapia have reduced appetite at D.O. < 1.5 mg/l).
3. Increased water acidity reduces food consumption.

Food:

4. Size of food. A finely divided food has a better conversion rate than a coarsely divided one.
5. Amount of food. An unlimited food supply may pass through the gut faster than a limited one and be only partially digested.
6. Composition of food. Foods with a high water or woody tissue content (e.g., leaves and potatoes) will have a less favorable conversion rate.
7. Method of presentation. Certain foods provide a better conversion rate if they are mixed than if they are presented separately (see Table 9).

Table 9

FOOD CONVERSION RATIO OF SOME FEED MATERIALS[a]

Foods of animal origin		Foods of plant origin			
Gammarus	3.9-6.6	Lupid seeds	3-5	Mill sweepings	8.0
Chironomids	2.3-4.4	Soyabeans	3-5	Rice flour	8.0
Housefly maggots	7.1	Maize	4-6	ditto	6-12
Fresh sea fish	6-9	Cereals	4-6	Manioc leaves	13.5
Fish flour	1.5-3.0	All cereals	5	ditto	10-20
Freshwater fish	2.9-6.0	Potatoes	20-30	Manioc flakes	17.6
Fresh meat	5-8	Potatoes	15	Household scraps	18.5
Liver, spleen and abbatoir offals	8	Maize	3.5	Colocasia leaves	23.7
		Cottonseed	2.3	Banana leaves	25.0
Prawns and shrimp	4-6	Cottonseed cake	3.0	Manioc flour	49.4
White cheese	10-15	ditto	2.5-5	Napier Grass	48.0
Dried silkworm pupae	1.8	Groundnut cake	2.7	Manioc rind	50.7
		ditto	2-4		
		Ground maize	3.5		
		Ground rice	4.5		
		Oil palm cakes	6.0		
		ditto	6-12		

Food mixtures			
Fresh sardine, mackerel scad, dried silkworm pupae	5.5	2/3 groundnut cake, 1/3 manioc leaves	3.5
Liver of horse and pig, sardine, silkworm pupae	4.5	1/2 manoic leaves, 1/2 ground rice	11.0
		2/5 manioc leaves, 3/5 manioc cosettes	12.8
Silkworm pupae silkworm faeces, grass, soyabean cake, pig manure, night soil	4.1	Cottonseed and manioc flour	5.1
		Leaves and fresh manure roots	26.8
Cortland Trout diet No. 6	7.1	Manioc leaves and household scraps	25.2
Raw silkworm pupae, pressed barley, Lema and Gammarus	2.55		

[a] From Hickling, 1962

Fish:

8. Size of fish. A small fish grows fast because its gut capacity is high relative to its body; this ratio decreases with increasing weight of fish.

9. Sexual maturity. Gonadal development reduces growth.

10. Stocking rate. Excessively high rates (crowding) will slow growth.

11. Fish species. Herbivores utilize some food materials better than carnivores.

Thus FCR's are crude empirical estimates and for local application only, especially when predicting the next fish crop.

FINFISH DIETS

Wild fish seldom show signs of nutritional diseases (Lovell, 1979b). However, under intensive pond culture, fish cannot rely solely on the limited natural food produced in ponds and must depend for healthy growth on diets that may be classified as complete or supplemental. These diets are evaluated on four basic criteria: (1) acceptability to fish, (2) effectiveness in promoting growth, (3) cost, and (4) availability.

Complete Diets

Dry or moist diets that contain all the essential nutrients in the correct proportions for fish growth are called complete diets. They usually contain 2 to 4 times the protein that terrestrial animal feeds contain, and they rely on fish meal as the principal protein source. Complete diets are normally fed to luxury fish like trout in intensive culture conditions where natural foods are limited or non-existent; however, fish cultured under high density pond conditions may also need a complete diet.

The first complete diets were made for salmon hatcheries in the early 1960's (Nose, 1979). At present, the formulas for most commercially prepared dry diets are generally unavailable to the public, but many institute formulas may be found in the literature (Halver, 1972; NAS, 1973, 1977). Examples are shown in Table 10.

Supplemental Diets

Since warmwater fishes are usually less valuable than the coldwater species (e.g., salmonids), they are grown more cheaply in ponds where natural food is available (Hepher, 1975). However, net fish yields on natural food alone are too low to cover fixed economic costs (Tal and Hepher, 1967) and supplemental feeding is normally necessary; it typically comprises about 50% of total production expenditues (Collins and Delmondo, 1976). If local waste materials like manure are available, costs may be significantly reduced.

Supplemental feeding is based upon three criteria: (1) the amount of natural food in the pond, (2) the nutritional requirements of the fish population in the pond, and (3) fish density. These points may be significantly influenced by other factors (seasonal condition, water temperature, fish size, etc.) that can cause enormous variation in the feeding requirements. Since no satisfactory method has yet been developed to assess the natural food produced in a pond and available to the fish, the formulation of a supplemental diet is even further complicated. Instead, most studies have concentrated on the standing stocks of natural foods, and not their rate of production or consumption by fish.

Hepher (1975) has pointed out that the three most important interrelated factors affecting fish production are stocking rates, fertilization, and supplemental feeding. The standing stocks of fish reach equilibrium at a pond's carrying capacity. Production increase can be realized only through enhanced feeding, either directly with supplemental feeding or indirectly through fertilization, or by reducing the stocking rate. In Israel, monoculture of common carp in unfertilized ponds yielded about 100 kg/ha; fertilization increased the carrying capacity to 460 kg/ha. In polyculture with Tilapia aurea it was further boosted to 600 kg/ha (Hepher, 1975).

Natural foods in intensive pond culture must be supplemented both quantitatively and qualitatively. The protein to energy ratio must be balanced, and a sufficient supply of vitamins and minerals added. The culturalist must always be aware that diet composition changes should accompany an increase in the standing stocks. For example, protein level requirements will increase with increasing standing stocks (Hepher, 1975). The deficit of growth factors in high densities are expressed by growth inhibition and lower feed utilization. For example, Hepher et al. (1971) found that the conversion rate of dietary protein to body protein in common carp increased from 4.5 at a density of 226-372 kg/ha to 12.2 at 372-461 kg/ha.

A considerable diversity of supplemental feeding patterns have evolved worldwide as a result of specific conditions, experience, and traditions. Locally available artificial feeds of plant or animal origin can often be obtained at nominal cost and efficiently utilized. China provides a good example. Tapiador et al. (1977) report that 60-70 kg of grass and vegetable tops can produce 1 kg of grass carp; 50 kg of snails and clams produce 1 kg of black carp; 100 kg of water fertilized with 77% bean curd residues and 23% fermented products residues produce 1 kg of silver carp; 500 g of fish waste produce 0.8 kg of silver or bighead carp; and 25 kg of animal manure produce 500 g of silver and bighead carp. Since grass and vegetables provide most of the supplemental feeds for fish, the pond dikes are used for plant cultivation. Experience indicates that 66.7 square meters of land is needed to provide 667 square meters of fish pond with plants as feed (i.e., 1:10).

Preparation of Foods

There are four basic methods of preparing foods for introduction into ponds:

1. The mechanical preparation (e.g., milling) of foods usually make them easier to chew and swallow, except when the particle size becomes so reduced that it is unavailable

Table 10a

COMPLETE DIET FORMULATIONS[a]

Ingredient	International feed no.	Amount in diet (%)
Forty-Percent-Protein Carp Grower		
Fish, meal mech extd, 65% protein[b]	5-01-982	46
Wheat, middlings, lt 9.5% fiber	4-05-205	28
Rice, bran w germ, meal solv extd	4-03-930	7
Wheat, bran	4-05-190	5
Soybean, seeds, meal solv extd, 44% protein[a]	5-20-637	5
Yeast, torula, dehy	7-05-534	4
Corn, gluten, meal	5-02-900	1.5
Vitamin premix[c]	--	0.5
Mineral premix[d]	--	0.5
Sodium chloride	--	0.5
Potassium phosphate	--	2.0
Twenty-Five Percent Protein[e] Catfish Pond Formula, Pelleted (Kansas Z-14)		
Wheat, bran	4-05-190	40.5
Sorghum, grain	4-04-383	17.5
Alfalfa, meal, s-c	1-00-025	10.0
Fish, meal mech extd	5-01-976	8.8
Soybean, meal, solv extd	5-04-604	8.5
Meat and bone meal (meat and bone scraps)	5-00-388	6.6
Corn, distillers solubles, dehy	5-02-147	5.0
Blood, meal	5-00-380	1.9
Dicalcium phosphate	6-01-080	0.57
Salt	6-04-152	0.5
Methionine, DL	--	0.09
Vitamin premix[b]	--	0.13

[a] From NAS, 1977

[b] 6.25 x percent nitrogen

[c] Vitamin premix: vitamins added to cellulose powder to make 0.5% of diet (mg/kg):

Choline chloride	500	Riboflavin	25
Ascorbic acid	80	Pyridoxine	8
Inositol	80	Thiamine hydrochloride	5
Niacin	60	Biotin	0.05
Calcium pantothenate	80	Vitamin A	8,000 (IU/kg)
Vitamin E	45	Vitamin D_3	1,500 (IU/kg)

[d] Mineral premix: added to cellulose powder to make 0.5% of the diet (mg/kg):

Manganese	25	Magnesium	250
Iron	10	Cobalt	3
Zinc	25		

[e] 6.25 x nitrogen

Table 10b

RECOMMENDED ALLOWANCE FOR VITAMINS IN SUPPLEMENTAL AND COMPLETE DIETS FOR WARMWATER FISHES[a]

Vitamin	Amount/kg dry diet[b]	
	Supplemental	Complete
Vitamin A activity	2,000 IU	5,500 IU
Vitamin D_3 activity	220 IU	1,000 IU
VItamin E	11 IU	50 IU
Vitamin K	5 mg	10 mg
Choline	440 mg	550 mg
Niacin	17-28 mg[c]	100 mg
Riboflavin	2-7 mg[c]	20 mg
Pyridoxine	11 mg	20 mg
Thiamin	0	0.1 mg
D-Calcium pantothenate	7-11 mg[c]	50 mg
Biotin	0	0.1 mg
Folacin	0	5 mg
Vitamin B_{12}	1-20µg	20µg
Ascorbic acid	0-100 mg[c]	30-100 mg[c]
Inositol	0	100 mg

[a] From NAS, 1977

[b] These amounts do not allow for processing or storage losses. Other amounts may be more appropriate for various species and under various environmental conditions.

[c] Highest amounts probably appropriate when "standing crop" of fish exceeds 500 kg/hectare of water surface.

for consumption by big fish (Woynarovich, 1975). It is thus recommended these foods be kneaded with water into a dough. There is some nutritional loss in mechanically prepared foods because they dissolve in pond waters more readily than whole grains. Another disadvantage is that small wild fish may eat a significant portion of the small food particles. Therefore, the necessity for mechanical preparation depends on the size of the fish to be fed.

2. Some foods, especially grains, are soaked (usually for several hours) before presentation to fish so that the food may swell, soften, and sink. Hickling (1962) recommends feeding in designated areas so that fish can learn where food will be introduced and so that the fish farmer can inspect the pond bottom to evaluate the amount of food consumption.

   It is not always necessary to soak hard food items. For example, whole lupin seeds, maize, and wheat can be fed to common carp during mid-summer when the fish are large and hungry. However, Tilapia will not eat maize until it is well soaked. Smaller size fish also require that ground or milled grains be soaked for optimal utilization.

3. Cooking or steaming of foods is an expensive method of preparation because of fuel costs and the labor involved. However, it is often unavoidable, especially with peas, beans, potatoes, and eggs. Cooked food is recommended for the feeding of fingerlings (Woynarovich, 1975).

4. Mixing food with other materials not only increases palatability and FCR (see Table 9), but may be necessary to complete the nutritional requirements of fish. In some cases, food is mixed with minerals (lime) or yellow clay to help prevent body defects like osteomalacia (Woynarovich, 1975).

Natural Feeds and the Role of Fertilization

There is no doubt that fertilization increases pond productivity (refer to the chapter on "Pond

Table 11

NUTRITIONAL VALUE OF FOUR ALGAE GROUPS[a]

(Composition of Four Major Groups of Algae and Their Relative Nutritive Value as Milkfish Food)

Group of algae	Number of samples	Total Composition: Total dry matter, %	Total Composition: Crude protein, %	Total Composition: Crude fat, %	Total Composition: Nitrogen-free extract, %	Total Composition: Fibre, %	Total Composition: Mineral matter, %	Digestive coefficient[b,c]: Crude protein, %	Digestive coefficient[b,c]: Crude fat %	Digestive coefficient[b,c]: Nitrogen-free extract, %	Digestive coefficient[b,c]: Fibre, %	Digestible[d] protein, %	Total digestible nutrients[e] %		Nutritive ratio[f]
Chaetomorpha															
Fresh form	15	8.54:	2.82	0.91	1.50	1.22	2.09	3	72	87	21	0.09	3.12	1	33.44
Detritial form	15	10.72:	3.46	0.38	3.21	0.98	2.69	66	89	85	37	2.28	6.13	1	1.66
Phytoflagellates[g]															
Fresh form	5	11.98:	3.91	1.32	5.61	0.42	0.72	81	91	78	23	3.17	10.41	1	2.37
Diatoms[h]															
Fresh form	15	12.87:	2.89	0.94	2.25	0.27	6.52	87	96	84	19	2.51	6.48	1	1.54
Filamentous blue-green algae[i]															
Fresh form	15	9.86:	2.32	0.21	1.52	0.70	5.11	69	86	81	38	1.60	3.49	1	1.18

[a] From Tang and Hwang, 1967

[b] Digestive coefficient: $\frac{\text{The amount of a class of organic nutrient in the feed - the amount of that class of organic nutrient in faeces}}{\text{The amount of that class of organic nutrient in the food}} \times 100$

[c] The water temperature during digestion experiments ranged from 29° to 33°C and the salinity from 24 to 27 ppt

[d] Digestible protein: The percentage of protein in the food x digestion coefficient of protein

[e] Total digestible nutrients: The sum of digestible protein, fibre, nitrogen-free extract and fact x 2.25

[f] Nutritive ratio: $\frac{\text{The percentage of total digestible organic nutrients - the percentage of digestible protein}}{\text{The percentage of digestible protein}}$

[g] Centrifuged from the pond water where Chlamydomonas and Chilomonas flagellates bloomed predominantly

[h] Furnished as the diatom sludge

[i] Collected from the pond bottom where the dominant genera, Oscillatoria and Lyngbya, grew

Fertilization Practices"). In the Congo, Hickling (1962) found that fish production declines after the initial application of fertilizers; if the practice is not regularly continued, feeding with leaves and household scraps will usually not improve the situation. The conclusion is that growth substances found in natural foods become depleted. For example, the addition of chironomid larvae and Daphnia to an experimental diet of Quaker oats and casein being fed to common carp noticeably increased their growth rates in excess of the nutritive value of these live foods (Yashouv, 1956). Hickling (1962) estimated that 50% of a common carp diet must come from natural foods versus 10% for Tilapia.

The promotion of natural foods through fertilization is quite evident in brackishwater ponds where benthic algal growth is desired for milkfish culture. In Taiwan, supplemental feeding is unnecessary when abundant algal pasture exists (Chen, 1970). However, when there is a shortage, especially during the rainy season when salinity decreases, rice bran, peanut meal, soybean meal, or flax seed cake are added. Generally the algal pastures consist of two groups of microscopic algae, the filamentous blue-green Cyanophyceae and the diatoms, Bacillariophyceae. In Table 11, Tang and Hwang (1967) have determined the nutritional information on four major groups of algae used as milkfish food in Taiwan.

It is estimated that the total amount of algal pasture grazed during the rearing season (April-October) for one fish is approximately 25,000 kg/ha (Tang and Chen, 1967).

In the Philippines, milkfish farmers collect algae from other water areas and transfer them into ponds when benthic growth is insufficient. Although green algae, Chlorophyta, are generally less nutritious than blue-greens the red seaweed Gracilaria appears very suitable for rearing fingerlings and adults. Many Philippine ponds grow milkfish to market size on a Gracilaria diet alone (Hora and Pillary, 1962). The nutritional information for some food algae and weeks are shown in Table 12.

In Malaysian freshwater ponds, Hickling (1962) estimated that 150 fingerling grass carp ate about 8600 kg of Napier grass (57 kg of Napier grass/fish) during a two month period; the crude conversion ratio was about 48:1. One advantage of culturing a herbivorous fish of this nature is the tremendous quantity of soft, partially digested feces it evacuates. This fecal material may be directly consumed by other fish species or serve as manure for the stimulation of plankton growth. The estimated amount of phosphorus recycled from the above Napier grass was 6.3 kg.

Larval Fish Diets

Larval fishes are usually cultured in rearing tanks rather than ponds and are often fed Artemia (brine shrimp). The increasing demand for Artemia has prompted efforts to find a suitable synthetic diet substitute that is not subject to seasonal and nutritional variation (Meyers, 1979). Two main techniques exist for the preparation of these diets (van Limborgh, 1979):

1. Preparation of a water stable matrix of dry ingredients followed by suitable grinding and sieving to proper paricle size (e.g., pellets, flakes).

Table 12

NUTRITIONAL VALUE OF CERTAIN ALGAE AND SEAWEEDS[a]

Name	Moisture, %	Ash, %		Fat, %		Protein, %		Carbohydrates, %	
		F[b]	D[c]	F	D	F	D	F	D
Gracilaria confervoides	6.92	15.31	16.48	0.4	—	11.98	12.89	65.39	70.63
Enteromorpha intestinalis	81.35	6.02	32.27	0.48	2.57	3.66	19.61	8.49	45.55
Chaetomorpha spp.	85.50	2.82	19.50	0.27	0.71	3.72	27.66	7.87	52.13
Cladophora spp.	57.20	9.90	23.16	0.84	1.96	5.16	12.07	26.90	62.81
Eichhornia crassipes	89.81	1.34	13.15	—	—	2.19	21.49	6.66	65.36

[a] From Hora and Pillary, 1962

[b] F - Fresh

[c] D - Dry

2. Incorporation of a solid, liquid, or finely suspended dietary component into properly sized micro-encapsulation.

It is important that nutritional loss be minimized during diet fabrication. Furthermore, as with fry and fingerling diets, the properties of water stability, density, size, color, taste, physical form, and attractants must be compatible with the feeding habits of larval fish.

ALTERNATIVE PROTEIN SOURCES FOR FISH MEAL

As mentioned above, the amino acid profiles of freshwater and marine fishes are quite similar. Thus fish meal is recognized as the best source of animal protein for most fish species. However, the increased costs and shortages of high quality fish meal impose very real constraints in the formulation of optimal diets. To emphasize the importance of finding a suitable fish meal substitute, Spinelli (1980) states that protein sources have been examined more intensely in the last 7 years than in the previous 50 years. Great differences exist in fish growth obtained from different sources of dietary proteins because of the different biological values in these proteins (Hepher, 1979).

Soybean Meal

Considerable work has been conducted with soybean meal, and it has met with limited success. Soybean meal presents fewer problems with herbivorous than with carnivoros fishes and in supplemental diets rather than complete diets.

Soybean contains about 47-50% protein, 5-6% ash, 1% lipids, and about 40% carbohydrates (Spinelli, 1980). It is deficient in tryptophan and the sulphur containing amino acids. Although coldwater rainbow trout can thrive on soybean diets enriched with free amino acids, the utilization of supplemental amino acids by the warmwater fish (channel catfish and carp) remains obscure (Nose, 1979). Either soybeans contain anti-growth factors or certain warmwater fishes cannot utilize free amino acids.

Table 13 compares the amino acid profiles of fish meal and soybean meal.

Soybean meal is low in phosphorus and trace metals and contains factors deleterious to fish and farm animals. Heat treatment de-toxifies these factors, but optimal guidelines for heat treatment have yet to be established (Nose, 1979). In addition, heat increases the acceptability of soybean meal to fish and improves the availability of nutrients. This is accomplished by deactivating trypsin inhibitors and by denaturing the proteins for better digestibility.

Single Cell Proteins (SCP)

Single cell proteins are usually derived from unicellular yeast and bacteria, but may also come from fungi and algae (e.g., Chlorella, Scenedesmus, Spirulina). They have a reasonably well-balanced amino acid profile (Table 13) and digestible lipids and carbohydrates (Spinelli, 1980). In addition they are an excellent source of vitamins and minerals.

Although many studies have been conducted with SCP (Spinelli, Mahnken, and Steinberg, 1979), it appears only algal SCP has been evaluated for warmwater pond fish culture. Hepher, Sandback and Shelef (1979) tested three different diet treatments, using three polycultured ponds for each treatment. All diets contained 25% crude protein; one contained fish meal, the second soybean meal, and the third algae meal (SCP). The yield from the algae meal diet was more than 10% higher than from the fish meal diet; the soybean meal diet showed the lowest yield (Table 14). The greatest differences occurred in fish which accepted supplemental feeds (common carp and Tilapia), whereas almost no growth differences were noted in the silver carp, which prefers only natural food. In effect, it appears that algae meal is the only known protein source that can replace fish meal in diets for the common carp and Tilapia. The obvious obstacle to full employment of SCP is the cost of producing, harvesting, and processing it.

Other Protein Sources

Table 15 summarizes alternative sources of protein that have been examined as partial or complete replacements for fish meal in aquaculture diets.

INFLUENCE OF FEED ON PRODUCT QUALITY

Few systematic studies have been made relating diet compositions to the organoleptic quality of fishes. However, observations show that fish can quickly concentrate organoleptically active compounds in their tissues. These produce off-flavors that later pose serious marketing problems. The organoleptic properties of pond cultured fish are influenced by many factors, as shown in Figure 1.

Most of the knowledge in this area has been derived from salmonids. There is very little basic and practical information available on pond cultured warmwater fishes. Lovell and Sackey (1973) found that blue-green algae can synthesize compounds that are readily absorped by channel catfish within two days. These compounds produce an earthy, musty flesh taste. The Actinomyces are also responsible for muddy taints in fish. Vale et al. (1970) compared kerosene-like tasting mullet (Mugil cephalus) with untainted mullet and found the flesh lipid content to be 15 and 7 percent respectively. A related finding was reported for common carp grown in ponds fertilized with liquid cow manure compared to those grown on grain or high protein pellets. The carp grown in fertilized waters had better flesh color than those fed on prepared diets; the intramuscular fat levels were 6 and 15-20 percent respectively (Moav et al., 1977). Silkworm pupae fed to the common carp can produce an undesirable flavor that can be purged from the flesh if pupae are eliminated from the diet for 30 days (Spinelli, 1979). As more is learned about the effects of nutrition, feeding, and environment upon the quality of fish flesh, it may be possible to develop supplemental rations that will favorably alter the organoleptic characteristics of the fish (Spinelli, 1979).

FEEDING PRACTICES

Feeding Behavior

The normal feeding habits of some warmwater cultured fish species are shown in Table 16. When fish feeding programs are developed, nutritional, economic, and feed preference aspects must be considered. For example, Cremer and Smitherman (1980) found that artificial feeds added to ponds were not consumed by silver carp, yet bighead carp enjoyed substantial growth; silver carp appear to accept only natural food (i.e., phytoplankton). Consequently, three types of feeding behavior in pond cultured fishes are recognized (Hora and Pillay, 1962):

1. Those that thrive on artificial food (e.g., grass carp, black carp).
2. Those that thrive best on a diet of both artificial and natural food (e.g., common carp, mud carp).
3. Those that take only natural food and not artificial food (e.g., silver carp).

Rates and Amounts of Feeding

Feeding strategies differ with many factors, which include fish species, type of feed, and intensive or extensive culture. Considerable care must be practiced, for excessive feeding is not only wasteful but also deleterious to water quality. Conversely, underfeeding limits the capacity for full growth. Nose (1979) recommends the floating type of feed to prevent excessive feeding. Knowing the rates of digestion or evacuation will lead to the establishment of feeding schedules similar to those used for trout, which utilize feeding tables based on water temperatures and flow rates. There are several reports (Nose, 1979) indicating that feeding in excess of twice daily has no beneficial effect on food conversion and growth in fish with true stomachs (channel catfish and rainbow trout); however, Tilapia nilotica, which has a

Table 13

AMINO ACID PROFILES OF ALTERNATE PROTEIN SOURCES[a]

Amino acid	Fish meal	SCP, yeast	SCP, bacteria	Fly larva	Soy meal, 47%
Alanine	6.34	5.28	6.32	6.15	4.33
Arginine	5.82	7.79	8.01	5.42	7.15
Aspartic	9.35	6.26	6.31	10.8	10.90
Cystine	0.70	0.54	0.50	0.82	0.61
Glutamic	13.3	8.79	6.21	12.2	17.5
Glycine	5.90	4.63	5.84	5.40	4.34
Histidine	2.22	2.34	3.26	3.50	2.90
Isoleucine	4.85	2.73	3.25	4.13	4.34
Leucine	7.35	4.48	4.66	6.95	7.33
Lysine	7.85	6.80	7.19	7.37	6.0
Methioniue	2.84	0.70	1.45	2.24	1.21
Phenylalanine	4.35	2.01	1.30	6.95	4.90
Proline	4.35	2.27	3.4	3.66	4.53
Serine	4.55	.97	2.73	4.51	5.22
Threonine	4.55	3.59	3.65	4.53	5.0
Tryptophane	1.33	0.60	1.00	1.45	1.21
Tyrosine	3.45	1.11	1.05	8.10	3.94
Valine	5.65	3.31	3.37	5.60	4.33

[a] From Spinelli, Mahnken, and Steinberg, 1979

Table 14

GROWTH ON FISH MEAL, SOYBEAN MEAL, AND ALGAE MEAL (SCP) DIETS[a]

Fish species	Fish meal diet		Soybean meal diet		Algae meal diet	
	Avg. harvest weight, g	Yield, kg/ha	Avg. harvest weight, g	Yield, kg/ha	Avg. harvest weight, g	Yield, kg/ha
Common carp	869.3	3196	1126.2	1921	992.8	3218
Tilapia aurea	433.8	614	402.8	621	431.6	700
Silver carp	1100.6	797	1051.9	739	1058.7	796
Bighead carp	878.3	119	918.2	140	1014.3	160
Total		4726		3421		4802
FCA[b]		2.1		3.6		2.1
C. carp (large)	398.8	1092	334.3	586	426.9	1556
C. carp (small)	159.9	589	156.4	566	190.6	631
Tilapia aurea	143.8	272	134.5	240	136.6	328
S. carp (large)	450.0	202	420.0	171	448.3	201
S. carp (small)	36.0	14	32.4	18	37.1	21
Grass carp	25.2	4	19.2	1	25.5	5
Total		2173		1582		2742
FCA[b]		2.0		2.8		1.7
Common carp		4877		3073		5405
Tilapia aurea		886		861		1028
Silver carp		1013		928		1018
Bighead carp		119		140		168
Grass carp		4		1		5
Annual Total		6899		5003		7624

[a] From Hepher, Sandback, and Shelef, 1979

[b] Feed conversion ratio = $\frac{\text{Total feed}}{\text{Yield of C. carp and Tilapia}}$

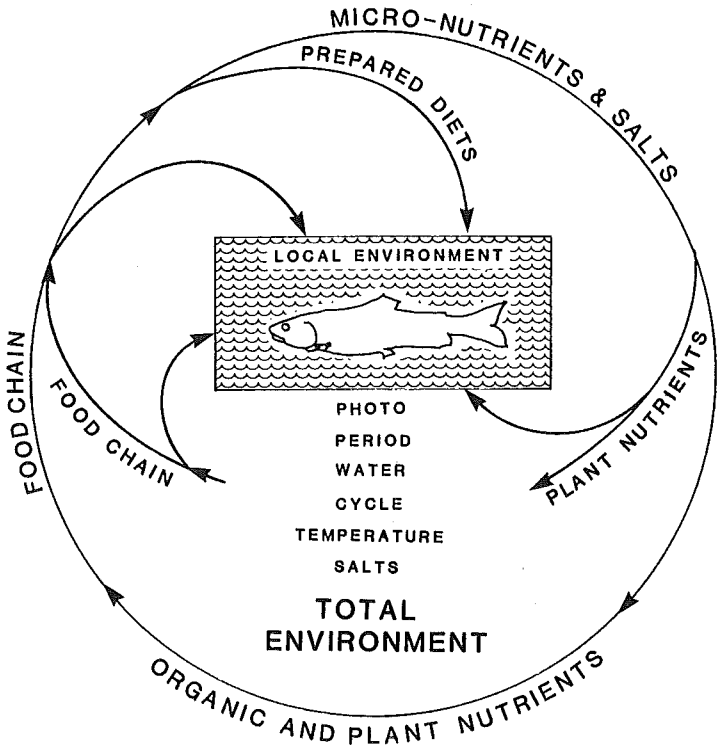

Figure 1

Factors affecting organoleptic qualities of fish. Figure from Spinelli, 1979.

true stomach (Balarin and Hatton, 1979), grew fastest when fed 4 to 8 times daily (Lovell, 1980). There is little information available for stomachless fishes like carp.

Shell (1967) found that the maximum growth rate of T. nilotica and T. mossambica fed 35 percent protein pellets does not necessarily accompany maximum feed utilization efficiency. These results possible reflect differences in the quality, formulation, and physical consistency of the food as well as the mechanics and frequency of feeding. Although these findings were for Tilapia grown in troughs, the same results might occur in ponds.

Nose (1979) recommends that, ideally, feeding tables should be based on the dietary energy requirements of the fish and the digestible or metabolizable energy value of the fish feeds. However, since this information is usually not available, conventional practice is to feed a fixed percentage based on total fish body weight. A typical example for T. nilotica culture in the Philippines is (Guerrero, 1980):

Fish Size	Feeding Rate
<50 g	5 percent
50-100 g	4 percent
>100 g	3 percent

According to Woynarovich (1975), when a pond population of common carp is unknown, the consumption of food supplied at specific feeding places within one hour indicates that about 1 percent of the total body weight was supplied or only the maintenance needs met; 3-4 hours is equivalent to 2-3 percent of the body weight; and 6-8 hours is equivalent to 4-5 percent of the body weight.

For feeding methods, it is generally not advisable to broadcast feeds, because much will be lost in the bottom muds. Broadcasting is acceptable only when the pond is small, the stock crowded, and the fish very hungry. The best practice is to establish 3-4 fixed feeding places per hectare (Woynarovich, 1975). If a boat is available, feeding in the interior of the pond is desirable; however, if only the shoreline is accessible, then the feeding area should not have soft mud and the water depth should range from 0.6-1.0 m. Hepher (1975) has described how feeding of cereal grains and pellets have become mechanized in many places. Container cars equipped with blowers, blow the feed into the pond at fixed points. A less costly innovation has been the use of demand feeders originally developed for channel catfish culture in the United States. It presently enjoys widespread success in Israeli ponds.

Table 15

POTENTIAL ALTERNATE PROTEIN SOURCES[a]

Commercialized		
Vegetable	**Animal**	**Not commercialized**
Soy meal	Poultry byproducts	Insect larvae
Rapeseed meal	Feather meal	Single cell protein
Sunflower meal	Shrimp and crab meal	Grasses
Oat groats	Blood flour	Leaf protein
Cottonseed meal	Fish silage	Vegetable silage
Wheat middlings	Meat meal	Zooplankton (krill, etc.)
		Recycled wastes
		Yeast
		Phytoplankton
		Bacteria
		Algae
		Higher plants
Protein (range), %		
15-50	50-85	4-85

[a] From Spinelli, 1980

Table 16

FEEDING HABITS OF SOME FISH SPECIES[a]

Feeding habit	Species
Algae and plankton	Silver carp
	Milkfish (Chanos chanos)
	Sarotherodon galileus
	Sarotherodon niloticus
	Grey mullet (Mugil cephalus)
Filamentous algae	Milkfish
Zooplankton	Bighead carp (Aristichthys nobilis)
Macrophytes	Grass carp (Ctenopharyngodon idella)
Benthos	Common carp (Cyprinus carpio)
	Black carp (Mylopharyngodon piceus)
	Mud carp (Cirrhina molitorella)
Detritus	Sarotherodon aureus
	Common carp
	Milkfish
	Sarotherodon niloticus
	Grey mullet

[a] From Schroeder, 1980

FUTURE RESEARCH NEEDS

There are many variations in culturing fish, not only between and within fish species, but also between countries. Further study is required for optimizing the quality and quantity of both natural and artificial feeds needed for maintenance and growth by different species of pond fish at different life history stages, stocking intensities, and under varied environmental conditions. Besides defining the effects of individual constituents in a diet, it is equally important to balance their quantitative aspects for optimal performance in the interconnecting metabolic systems involved in growth. In addition, studies are needed of feed form, texture, size, smell, methods of feed distribution, and on the feeding behavior of fish at different life stages.

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POND PRODUCTION SYSTEMS: WATER QUALITY MANAGEMENT PRACTICES

by

Arlo W. Fast

INTRODUCTION

Water quality for aquaculture is defined here simply as "the degree of excellence that a given water possesses for the propogation of desirable aquatic organisms." The required quality is a function of the specific culture organisms and it has many components that are complexly interwoven. Sometimes a component of water quality can be dealt with individually, but because of the complex interactions of components one must usually view the total array and attempt to determine which components are critically limiting the culture organisms. Often, several components must be manipulated simultaneously to achieve a stable improvement in the "degree of excellence."

Water quality is one of the most important factors affecting successful pond fish culture. If water quality is excellent, then survival, growth and reproduction can achieve high values; otherwise fish production will be reduced or impossible.

Some of the more commonly cultured warmwater pond fish species are relatively tolerant of poor water quality. They can exist and grow over a wide range of salinity and temperature, and they can tolerate low oxygen concentrations for brief periods (Table 1). Those species were undoubtedly selected by early aquaculturists for their hardiness. The milkfish, for example, can be reared over a salinity range of less than 10°/oo to more than 150°/oo (more than 4 times the salinity of seawater). Mullet and tilapia can be reared in fresh or marine waters, and all three are tolerant of low oxygen conditions. All of the other commonly cultured species, especially the carps and catfish, are very tolerant of low oxygen. Most are freshwater species, although they are also reared in brackish water.

Maximum fish growth occurs with warm waters, high rates of photosynthesis (or feeding rates), a large range in oxygen fluctuations, and with water quality conditions far from pristine. High quality water for fish culture would not meet water quality standards for domestic drinking water. We must therefore keep in mind the intended use of the water and the water quality necessary to meet the intended use.

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Many potential water quality problems can be avoided by proper pond siting. Ponds sited on unsuitable soil types, in areas with water of inadequate quantity or quality, or where temperature or salinity are too high or low are doomed to failure or marginal success. The time and money required to evaluate a potential site thoroughly are worth the investment. This evaluation will usually detect potential water-quality problems before they occur and thus allow the aquaculturist to select a better alternative site if there is one.

There are a very large number of possible pollutants[1] that can deleteriously affect aquacultural operations. Many authors credit industrial pollution and an uncontrolled world population increase for the substantial reduction in both wild fish stocks and aquaculture potential (Bardach 1978; Borgstrom 1978; Chen 1976). The list of these pollutants is indeed long. Some of the more better known pollutions are reviewed by McKee and Wolf (1963), Environmental Protection Agency (1971, 1976), National Academy of Science and National Academy of Engineering (1972), Thurston et al. (1979), Colt et al. (1975), and Friedman and Shibko (1972).

In this chapter I will describe some of the more important components of water quality and discuss their management practices. Although we dissect each component individually, bear in mind that these are not mutually exclusive aspects and that the management of one aspect will affect others.

For further information on water quality principles and practices, you should refer to the publications cited in this review. Water Quality in Warmwater Fish Ponds by Dr. Claude E. Boyd (1979) is particularly well written and an excellent resource publication. This review relies heavily on that publication for illustrations.

[1] Pollutants normally refer to substances or conditions caused by man, but we use the term here to include both natural and man-induced situations.

Table 1

SALINITY, TEMPERATURE AND DISSOLVED OXYGEN VALUES FOR SELECTED WARMWATER POND FISHES[a]

	Salinity,[b] %			Temperature, °C			Min. Oxygen, mg/l	References
	Min.	Optimum	Max.	Min.	Optimum	Max.		
Chanos Milkfish	F	10-50	157	12-15	25-36	39-41	1.5	Schuster, 1960; Bardach et al., 1972; Helfrich, pers. comm.; Crear, pers. comm.; Crear, 1980
Mugil Mullet	1	18	50	5	21-33	35-40	2.5-7.0	Abbott, pers. comm.; Kuo, 1979; Kuo et al., 1975;
Chlarias Catfish	F		S	24	29-32	32	2.5	Duodoroff and Shumway, 1970; Bell and Canterbery, 1976; Hora and Pillay, FAO 1962; Collins, 1977
Ictalurus punctatus Catfish	F		8-12	8-20	25-30	39	0.8-2.0	Duodoroff and Shumway, 1970; Colt et al., 1970
Tilapia and Sarotherodon Tilapia	--[c]	0-35	69	10-15	25-33	35-42	0.2-2.0	Balarin, 1979
Cyprinus carpio European carp	F		11	0-3	20	35	0.2-2.8	Duodoroff and Shumway, 1970; Nakamura, 1948; Black, 1953; Sigler, 1958; La Rivers, 1962; Needham, 1950; Burns, 1966
Ctenopharyngodon idella Grass carp	F		7-10	12.8	18.3-29.4	35.5	0.2-0.6	Hickling, 1962; Duodoroff and Shumway, 1970; Kilambi and Robinson, 1979; Hora and Pillay, FAO 1962;
Hypophtalmichthys molitrix Silver carp	F		7-10	15	20-28	30	0.3-1.1	Hickling, 1962; Duodoroff and Shumway, 1970; Hora and Pillay, 1962; Ling, 1977; Chen, 1976
Carp polyculture	F		--[c]	21.5	--[c]	--[c]	4	Dimitrou, 1974
Common carp, Grass carp, Bighead carp and Silver carp	--[c]	--[c]	--[c]	21	27-29	32	0.5	Bortz, Ruttle and Podems, 1977
Catla catla Indian carp	F		13	14.4	26-29	34	0.7-1.0	Hickling, 1962 Duodoroff and Shumway, 1970; Bell and Canterbery, 1976; Hora and Pillay, FAO 1962

[a] Salinity and temperature values are generally for long-term periods (e.g. months), whereas minimum oxygen values are generally for less than one day.

[b] F = freshwater, S = slightly brackish. [c] Information not available to author, or not determined.

Sampling practices or analytical procedures are not covered in this treatise. These are covered thoroughly elsewhere, especially in "Standard Methods for the Examination of Water and Wastewater," American Public Health Assoc. et al. (1971, 1976); Boyd (1979); and Limnologist Methods, Welch (1948). Limnological concepts and principles are also important for the understanding of pond ecology, or how the pond functions. These are covered in more detail in Welch (1952), Ruttner (1953), Hutchinson (1957, 1967, 1975), Cole (1975), Wetzel (1975), and Moss (1980).

Through the remainder of this chapter discussion of some of the water-quality parameters and practices will be restricted to those that are considered particularly important and useful. Lastly, a few problem areas worthy of further research are listed.

DISSOLVED OXYGEN (DO)

Dissolved oxygen concentration is one of the most important water-quality parameters. Oxygen depletion is usually the principal cause of sudden, massive fish kills. Maintaining a "normal" or desirable oxygen regime in a pond not only helps assure the fish's health, but also indicates that the pond system is functioning suitably.

A productive pond will typically have supersaturated DO during the late afternoon, and undersaturated DO at dawn (Fig. 1). This daily cycle may range between 200% and 25% of saturation. Most warmwater pond fishes are quite tolerant of temporary low oxygen concentrations (Table 1). Maximum fish production rates are possible under these conditions provided that the nighttime DO does not fall below 1 to 2 mg/1. Oxygen concentrations below this range indicate that undesirable conditions are developing in the pond and that corrective actions may be necessary.

Supersaturated DO has been implicated in fish kills (Weitkamp and Katz, 1980), but supersaturation is not normally lethal. However, highly supersaturated DO during the day may indicate depletion to near zero at night due to the respiration of the dense plant population necessary to produce the supersaturation.

We can better understand how DO depletion occurs in a fish pond if we describe the interactions between the main variables which result in the daily DO cycle (Fig. 2). These variables include: Photosynthesis, Diffusion and Respiration.

A healthy, dense plant population will produce large amounts of DO by photosynthesis, and thus cause DO supersaturation during the day. Photosynthesis is

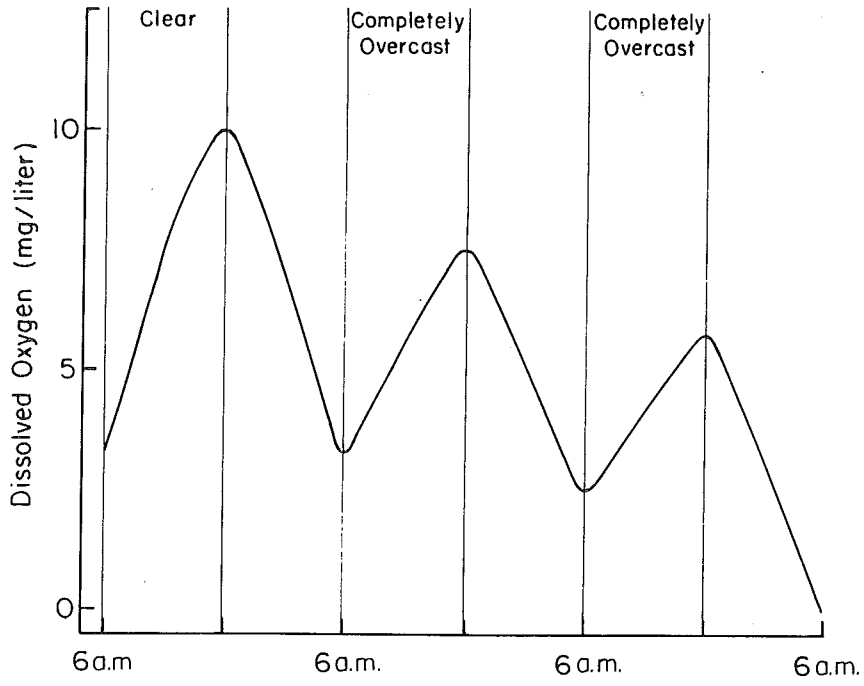

Figure 1

Characteristic dissolved oxygen cycle in a fish pond. Maximum DO occurs in the afternoon due to photosynthetic oxygen production, while DO minimum occurs at dawn due to nighttime respiration. Overcast weather can reduce photosynthesis and lead to oxygen depletion during the night. Figure from Boyd (1979).

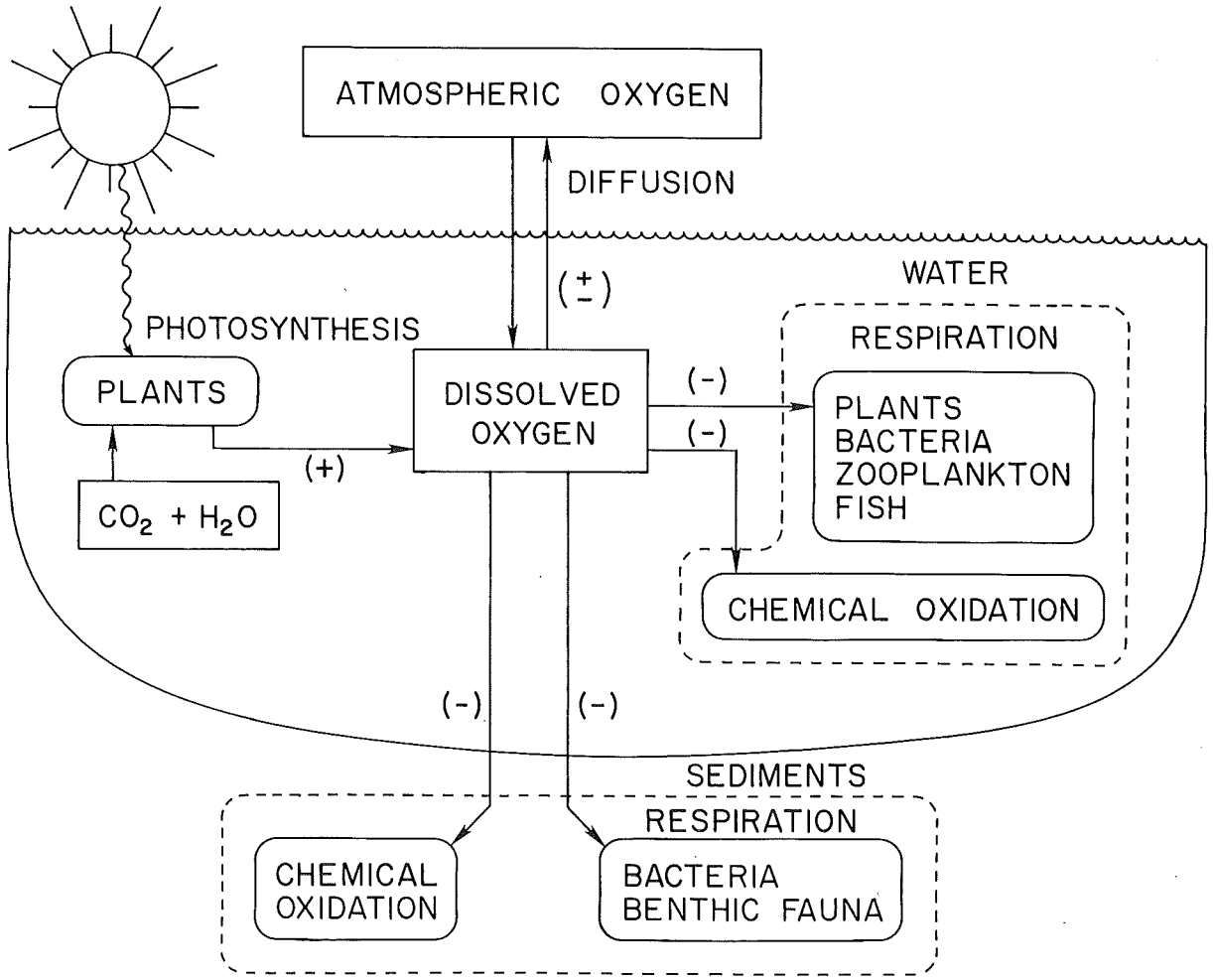

Figure 2

Principal sources and sinks for dissolved oxygen in a fish pond.

often the principal source of oxygen and in a healthy pond it exceeds the rate of oxygen consumption or losses during a daily cycle (Fig. 2).

Oxygen may be either gained or lost through diffusion into or out of a pond. Oxygen diffuses into the pond (gain) from the atmosphere when the pond water is undersaturated with oxygen. DO saturation values are largely a function of water temperature, elevation (barometric pressure), and salinity (Table 2). Oxygen diffuses out of a pond (a loss) when the DO in the pond is supersaturated. The rate of diffusion in or out increases substantially the greater the DO deviates from 100% saturation. This rate of diffusion (and direction) is shown in Table 3 (Schroeder 1975, Boyd 1979). For example, a pond with only 50% DO saturation at dusk will gain 1.69 mg/l during the night, whereas a pond with 250% DO saturation at dusk will lose 2.9 mg/l of DO during the night.

The respiratory consumption of DO by fish, plankton, and other organisms living in the water or on or in the sediments accounts for the greatest DO loss from the pond water. This oxygen is used to maintain aerobic metabolism and is converted to CO_2 and other products.

Mud respiration may range between 8 and 125 mg $O_2/m^2/hr$ (Mezainis 1977, Schroeder 1975). For a 1-meter deep pond, these values correspond to oxygen consumption rates from the water of 0.1 and 1.5 mg O_2/l per 12 hours. Much higher oxygen consumption rates by the mud are possible if the mud is suspended in the water, or if excessive amounts of organic materials (e.g. manure or feed) are added to the pond.

Fish respiration is primarily related to fish density (kg/hectare) and water temperature. Respiration rates typically range between 65 and 888 mg O_2/kg of fish/hour (Boyd 1975). Thus if a 1-meter deep pond stocked with 4,000 kg of fish/hectare contains fish respiring at 400 mg O_2/kg/hr, the oxygen consumption in the pond from fish respiration would equal 1.9 mg $O_2/l/12$ hrs.

Table 2

SOLUBILITY OF OXYGEN (mg/l) IN WATER AT DIFFERENT TEMPERATURE, ELEVATION AND SALINITIES
(Dissolved Oxygen Values Are for 100% Saturation in Water Exposed to Water-Saturated Air)

Temperature, °C	Elevation, ft (m)									
	0 (0)	500 (152)	1000 (305)	1500 (457)	2000 (610)	2500 (762)	3000 (915)	3500 (1067)	4000 (1220)	4500 (1372)
0	14.6	14.3	14.1	13.8	13.6	13.4	13.1	12.9	12.6	12.4
5	12.8	12.5	12.3	12.1	11.9	11.7	11.5	11.2	11.0	10.8
10	11.3	11.1	10.9	10.7	10.5	10.3	10.1	9.9	9.8	9.6
15	10.1	9.9	9.7	9.5	9.4	9.2	9.0	8.9	8.7	8.6
20	9.1	8.9	8.8	8.6	8.4	8.3	8.1	8.0	7.8	7.7
25	8.2	8.1	8.0	7.8	7.7	7.5	7.4	7.2	7.1	7.0
30	7.5	7.4	7.3	7.1	7.0	6.9	6.7	6.6	6.5	6.4
35	6.9	6.8	6.7	6.6	6.4	6.3	6.2	6.1	6.0	5.8
40	6.4	6.3	6.2	6.0	5.9	5.8	5.7	5.6	5.5	5.4

	Salinity, parts per thousand									
	0	5	10	15	20	25	30	35	40	45
0	14.6	14.1	13.6	13.2	12.7	12.3	11.9	11.5	11.1	10.7
5	12.8	12.3	11.9	11.6	11.2	10.8	10.5	10.1	9.8	9.5
10	11.3	10.9	10.6	10.2	9.9	9.6	9.3	9.0	8.8	8.5
15	10.1	9.8	9.5	9.2	8.9	8.6	8.4	8.1	7.9	7.6
20	9.1	8.8	8.6	8.3	8.1	7.8	7.6	7.4	7.2	7.0
25	8.2	8.0	8.8	7.6	7.4	7.2	7.0	6.8	6.6	6.4
30	7.5	7.3	7.1	6.9	6.8	6.6	6.4	6.2	6.0	5.9
35	6.9	6.8	6.6	6.4	6.2	6.1	5.9	5.8	5.6	5.5
40	6.4	6.2	6.1	5.9	5.8	5.6	5.5	5.4	5.2	5.1

[a] Data from Colt, 1980 and Weiss, 1970

Respiration of plankton and bacteria in the pond water (BOD) may range from 0.02 to 0.7 mg/l/hr, with an average between 0.1 and 0.3 mg/l/hr (Schroeder 1975, Boyd 1979). This water BOD could range from 0.24 to 8.4 mg/l/12 hrs.

From the foregoing, we see that nighttime oxygen depletion from respiration could equal:

O_2 consumption, mg/l/12 hrs

	Min.	Max.
Mud	0.1	1.5
Fish	0.3	4.2
BOD	0.2	8.4
	0.7	15.2

If the rate of respiration is near the higher value, and if DO at dusk is less than 16 mg/l, then oxygen depletion to near zero could occur before dawn.

From the above values, water BOD has the greatest potential for depleting DO. Most often high BOD corresponds to the decay of a dense growth of phytoplankton or macrophytes. The plants' death not only deprives the pond of its principal source of oxygen (photosynthesis), but it also creates a greatly increased water BOD due to the decay and the bacterial respiration on the dead plants. Mass death of plants often occurs for unknown reasons. Other times their death or moribund condition is caused by inclement weather or by toxic substances entering the pond. Substances (such as herbicides or algicides) may be non-toxic to the animals at certain concentrations but very toxic to the plants.

Dissolved Oxygen Management Techniques

There are a number of possible means to avert excessive oxygen depletion or to correct low DO when it does occur.

Predicting a low DO level is highly desirable and should minimize fish losses. Romaire et al. (1978) and Boyd (1979) describe a predictive procedure for catfish and tilapia ponds based on water temperature, fish density (lb/acre) and DO concentration at dusk. Pond secchi disc or chemical oxygen demand (COD) values are used to predict safe or unsafe DO conditions. One example of this technique is shown in Table 4 for 1,000 lb/acre of channel catfish, and for safe and unsafe secchi disc values. This predictive procedure is applied at dusk each day.

Table 3

PREDICTED GAINS (+) AND LOSSES (-) OF DISSOLVED OXYGEN FROM FISH POND DURING THE NIGHT BASED ON OBSERVED OXYGEN SATURATION AT DUSK. (These Values Are For a 1-m Deep Pond, For a 12-Hour Period.)[a]

DO concentrations at dusk, % of air saturation	Gain or loss of DO during the night, mg/L
50	+1.69
60	+1.49
70	+1.18
80	+1.00
90	+0.77
100	+0.44
110	+0.16
120	-0.18
130	-0.55
140	-0.94
150	-1.48
160	-1.64
170	-1.82
180	-1.98
190	-2.11
200	-2.37
210	-2.42
220	-2.54
230	-2.67
240	-2.76
250	-2.91

[a] Table from Boyd, 1979, modified from Schroeder, 1975

Another predictive technique involves measuring DO concentrations during the night and then projecting minimum DO values at dawn (Figure 3, Boyd 1979). This procedure gives less lead time than the previous procedure, but it can be useful in some cases, and it does not require much knowledge of pond-specific conditions like fish standing crop.

Familiarity with the pond is equally important. An aquaculturist with intimate knowledge of the pond's behavior and history can often predict oxygen depletions, fish diseases, or other problems before they strike. Water color and fish behavior are clues. This knack is difficult to quantify, but is an essential part of most successful aquaculture projects.

Continuous aeration or circulation of pond water is another technique for preventing DO depletion, while at the same time increasing fish production. Loyacano (1974) increased average oxygen concentrations from 3.1 mg/l in non-aerated ponds to 4.5 mg/l in ponds continuously receiving 10.4 m^3 min/ha of compressed air (Table 5). Fish production was respectively increased from 2,736 kg/ha to 5,510 kg/ha. Busch and Goodman (in press) artificially circulated a catfish pond 18 hours each day with a low energy paddlewheel device. Compared with a noncirculated pond, oxygen concentrations were higher in the circulated pond, and fish production was 4,540 kg/ha in the circulated pond vs. only 3,450 kg/ha in the noncirculated pond. Emergency aeration was required on several occasions in the noncirculated ponds to prevent serious DO depletion and fish kill. The net result was that continuous circulation required less total energy and was less expensive than the emergency aeration in the noncirculated pond ($54.89/ha vs. $91.60/ha).

The mechanism whereby continuous aeration or circulation causes higher DO and greater fish production is not well understood. However, it could be related to two factors:

1. Continuous circulation reduces thermal stratification and thereby helps maintain aerobic conditions throughout the pond. This should result in a more constant decomposition of organic matter and even distribution of respiratory load.

2. Continuous circulation may also result in more oxygen diffusion into the pond and may help prevent phytoplankton die-offs. These die-offs greatly reduce the photosynthetic input of DO to the pond and at the same time greatly increase the respiratory load due to decomposition of the algae. Boyd (1975, 1979) found that these die-offs were invariably associated with dense growths of blue-green algae and calm, clear, warm weather. The calm weather allowed the blue-greens to float to the water's surface where intense sunlight killed them. A system of continuous circulation could prevent this occurrence.

Excessive fertilization from inorganic fertilizers, manures, feeds, or watershed run-off is another cause of oxygen depletion. Excessive fertilization normally leads indirectly to oxygen depletion by causing excessive algal growth. Excessive algal growth in turn can lead to DO depletions should the algae die suddenly. Controlled fertilization is a means of preventing DO depletion.

Table 4

CRITICAL SECCHI DISC DEPTHS (in cm) FOR A 1-METER DEEP FISH POND AS A FUNCTION OF WATER TEMPERATURE AND DISSOLVED OXYGEN CONCENTRATION AT DUSK[a,b]

Temperature, °C	DO concentration at dusk, mg/L										
	2	3	4	5	6	7	8	9	10	11	12
20	37	S	S	S	S	S	S	S	S	S	S
21	58	26	S	S	S	S	S	S	S	S	S
22	79	42	21	S	S	S	S	S	S	S	
23	90	58	32	16	S	S	S	S	S	S	S
24	100	69	42	26	S	S	S	S	S	S	
25	100	79	53	37	21	S	S	S	S	S	S
26	100	85	63	48	32	16	S	S	S	S	S
27	100	90	69	53	37	26	S	S	S	S	S
28	100	95	74	58	45	32	21	S	S	S	S
29	100	95	79	63	53	40	29	18	S	S	S
30	100	100	85	69	58	45	34	26	16	S	S
31	100	100	87	74	63	50	40	32	21	S	S
32	100	100	90	79	66	55	45	37	29	18	S

[a] Table from Boyd, 1979.

[b] In the example, the pond contained 1,120 kg/ha (1,000 lb/acre) of channel catfish. Observed Secchi disc values of less than the table values indicate that DO concentrations will drop below 2 mg/l by dawn. An (S) indicates that DO will not drop below 2 mg/l regardless of observed Secchi disc values.

Emergency Aeration

Once the DO drops to a dangerously low value (e.g. 1-2 mg/l) and the fish show signs of distress, quick action must be taken to prevent fish loss. There are several emergency-aeration techniques. 1. Flushing. Flushing of high DO water into low DO pond water is effective and inexpensive, provided an adequate supply of high DO water is available. Sources of such water include nearby streams, wells, ponds, or coastal waters. Gravity flow is the least expensive, but not often available. The water normally must be pumped, and most often from adjoining fish ponds. 2. Mechanical aeration. Emergency aeration may be achieved by either injecting air into water or by spraying the water into the air. The latter technique is more efficient in terms of kg O_2 dissolved per kw-hr (Rappaport et al. 1976, Boyd and Tucker 1979, Busch et al. 1974). Emergency aeration devices include: paddlewheel aerators that circulate and splash water into the air; floating sprayer types that pump water from below the surface and spray it into the air; air blowers that inject air either at one point in the pond or through a perforated pipe; large-volume water pumps that pump water from the pond (or another source) and spray it into the air above the treatment pond; and venturi aerators that suck air into a pipe through which the low DO water is pumped. Of these systems the paddlewheel design is generally considered the most effective.

Two other mechanical aeration devices that utilize pumped water (or gravity flow) are the inclined plane and the packed column. Wirth (1981) described the use of an inclined plane, or cascade aerator, to prevent winterkill in Wisconsin lakes. This aerator is trailer mounted and may be towed to location. It measures 2.4 m (8 ft) wide by 11 m (36 feet) long and is basically a rectangular box with baffles. In operation, the box is tilted so that the upper end is about 2.4 m (8 ft) above the ground. Wirth pumped 38 m^3/min (10,000 gpm) through this aerator and brought the DO from 1 to 11 mg/l on one pass. Owsley (1978) describes a packed-column aeration device which effectively increased DO to saturation while at the same time reducing the concentration of other gases like nitrogen (N_2). The packed column consists of a pipe packed with plastic elements. Water cascades through the aerator and forms a thin surface film on the plastic elements. This increases oxygen transfer between the air in the packed column and the water. Both the inclined plane and the packed column aerators may have special uses for emergency pond aeration. 3. Partial aeration. Most emergency aeration devices are intended or designed to aerate the entire pond. This may not be necessary. Aeration of only a portion of the pond is an alternative. The major advantage of partial aeration is that a much smaller aeration system is needed.

To the best of my knowledge, partial aeration has not yet been attempted. It could be used if a removable partition could be quickly installed when aeration is needed (Fig. 4). A plastic sheet suspended from a float line should suffice. Holes in the plastic would permit entrance of the fish. The fish will readily home on the higher DO within the sheet. They would remain within the aerated portion until the DO was again suitable in the larger pond area, at which time the sheet could be removed and the fish dispersed. Partial aeration could be used with any of the aforementioned aeration devices. The device should be portable so that it could be moved to the affected ponds. This technique may have special applications in very large ponds that would be difficult and expensive to aerate otherwise.

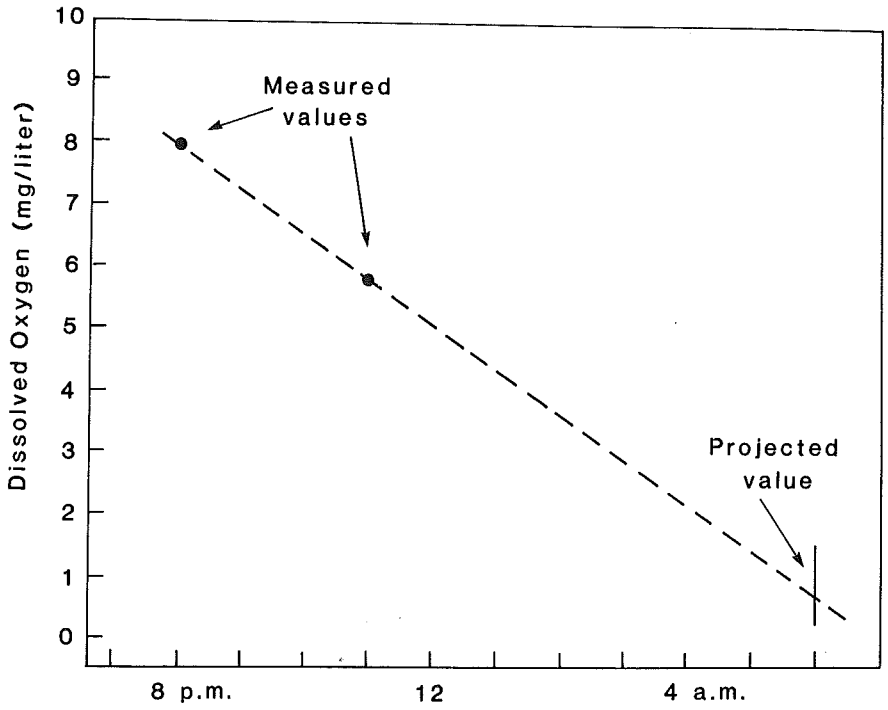

Figure 3

A method for predicting minimum dissolved oxygen during the night. This method requires at least two DO observations during the night. Figure from Boyd, 1979.

TEMPERATURE

Effects on Fish Growth

Water temperature has a profound influence on the species of fish that can be cultured, growth rates, the quality of the fishes' flesh, food conversion efficiency, and the economics of a fish culture operation.

Fish typically have a series of growth curves related to water temperature and feeding rate (Fig. 5). These curves show a maximum growth rate for a given temperature and feeds rate. For example, when sockeye salmon are fed in excess they have amaximum growth rate of 1.4% of their body weight per day, at a temperature of about 15°C. At temperatures above or below 15°C, or at lower feed rates,

Table 5

AVERAGE FISH PRODUCTION RATES, AVERAGE FISH SIZE, AND AVERAGE OXYGEN CONCENTRATIONS IN WHITE CATFISH PONDS RECEIVING THREE LEVELS OF ARTIFICIAL AERATION[a,b]

Air injection volume, m^3/min•ha	Average fish production rate, kg/ha	Average fish size, g	Average oxygen concentration, mg/l
0	2,736	194	3.1
6.9	4,562	287	3.9
10.4	5,510	317	4.5

[a] Date from Loyacano, 1974.

[b] Air injection was continuous in the aerated ponds. Twelve ponds (four for each aeration level) were used.

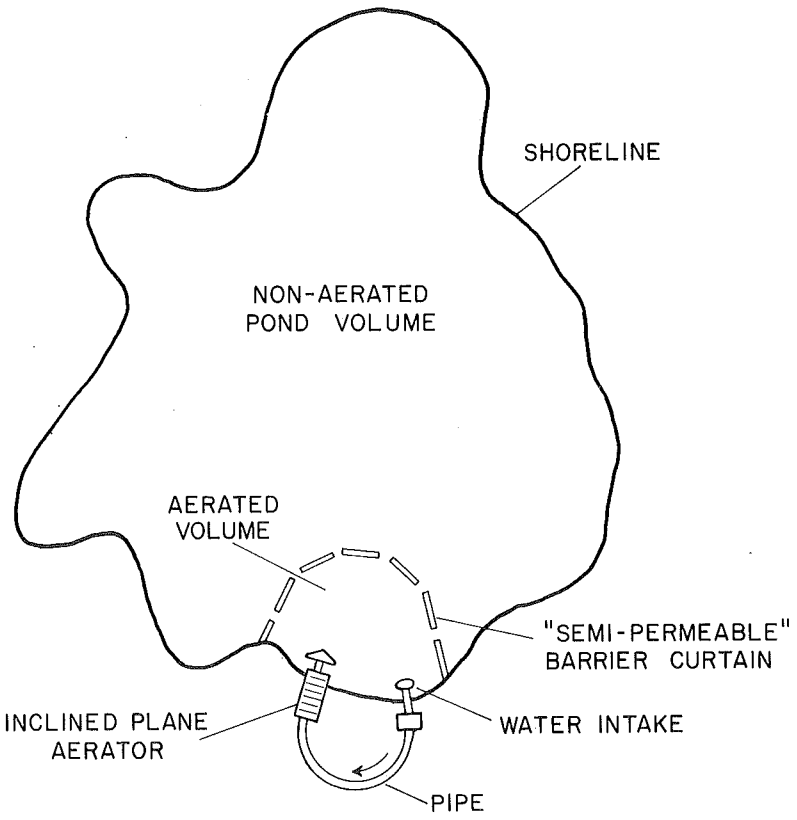

Figure 4

A proposed technique for partial aeration of a fish pond. The aerated portion is separated from the main pond area by a semipermeable barrier. An inclined plane aeration system is shown in the aerated volume, although other aeration devices could be used.

growth is reduced. These growth data can be further refined to establish the most efficient or economical set of conditions for a given species (Brett et al. 1969). Although the curves shown in Figure 5 are for sockeye salmon, other species have similar curves with different values.

Colt et al. (1975) reviewed temperature effects on channel catfish. They report that channel catfish: cease feeding below 8 to 10°C; have optimum secretion of digestive enzymes at 23.9°C and maximum digestion rates between 26 and 30°C; show optimum growth near 30°C and decreasing growth above 32°C (even with unlimited feed); and have an upper lethal temperature of 39°C. In addition, the "quality" of the catfish also changes as a function of temperature. They report a linear increase in the whole carcass fat content of channel catfish from 23.8% to 43.6% in fish reared over the temperature range of 18 to 34°C.

Although such details are largely unknown for most commonly cultured warmwater fish species, it is generally known over what temperature range a fish species performs best. A fish culturist should try to site ponds in a location that will maximize the growth potential for the target species. Conversely, if the ponds are already existent or must be sited at a given location, then species that are best suited for these conditions should be selected. Application of this advice may require the accumulation of site-specific temperature data for a year or more if the data does not already exist for comparable sites. This can save the considerable expense of an unsuitable site.

It is usually impractical to heat or cool water artificially. The energy requirement is great, especially if the water has much flow-through. However, some unique situations exist whereby the aquaculturist can capitalize on natural or man-made conditions to optimize his water temperatures for fish culture. Springs or wells often contain water of an ideal and uniform temperature. This has led to the establishment of a large trout industry in Idaho (Klontz and King 1974). Power plant cooling waters can yield temperatures nearly ideal for the growth of warmwater fish (Guerra et al. 1979, Ford et al. 1975). Fast (1977, 1979) has proposed a system of fish culture that capitalizes on natural thermal stratification in lakes, quarries, reservoirs, or the ocean. By selective depth withdrawal within a thermally stratified water body,

optimum water temperatures and natural feed items may be provided nearly year-round. Lastly, many tropical or subtropical locations like Hawaii have nearly ideal water temperatures year-round for many warmwater species. Not only is the temperature near the optimum for feed conversion and growth, but there is little seasonal fluctuation in temperature, light, or other conditions required to maintain a highly productive pond ecology.

Thermal Stratification

Thermal and chemical stratification can develop in even shallow ponds. Boyd (1979) observed diurnal thermal stratification in shallow ponds averaging 1-m deep at Auburn, Alabama, where they "stratify during daylight hours in warm months only to destratify at night when the upper layers cooled. Larger, deeper ponds (0.5 ha or more with average depths of 1.5 to 2.0 m) may remain stratified throughout the warm months." In Boyd's shallow ponds, oxygen depletion may occur over much of the pond bottoms during a part of each day. In the deeper ponds, the oxygen may become depleted over much of the pond bottoms for much of the summer (Fig. 6 and 7).

The effect of this stratification on pond productivity is not well documented. However, it is reasonable to assume that such stratification could render these bottom areas uninhabitable to the fish, as it does in deeper water bodies (Miller and Fast 1981). It may also reduce the production of benthic forage organisms and/or make these organisms largely unavailable to the fish (Fast 1973). If this happens, then productivity could be substantially reduced, especially in cases where the fish obtain a considerable portion of their diet from food produces by the pond.

The few studies where continuous aeration or circulation of the pond was attempted indicate the artifical mixing will increase fish production (Loyacano 1974; Busch and Goodman, in press). These studies are also discussed in the section on dissolved oxygen. Although neither study thoroughly documented the effect of continuous mixing on thermal stratification, benthic oxygen concentrations, benthic fauna population, and fishes feeding behaviors, the implication is

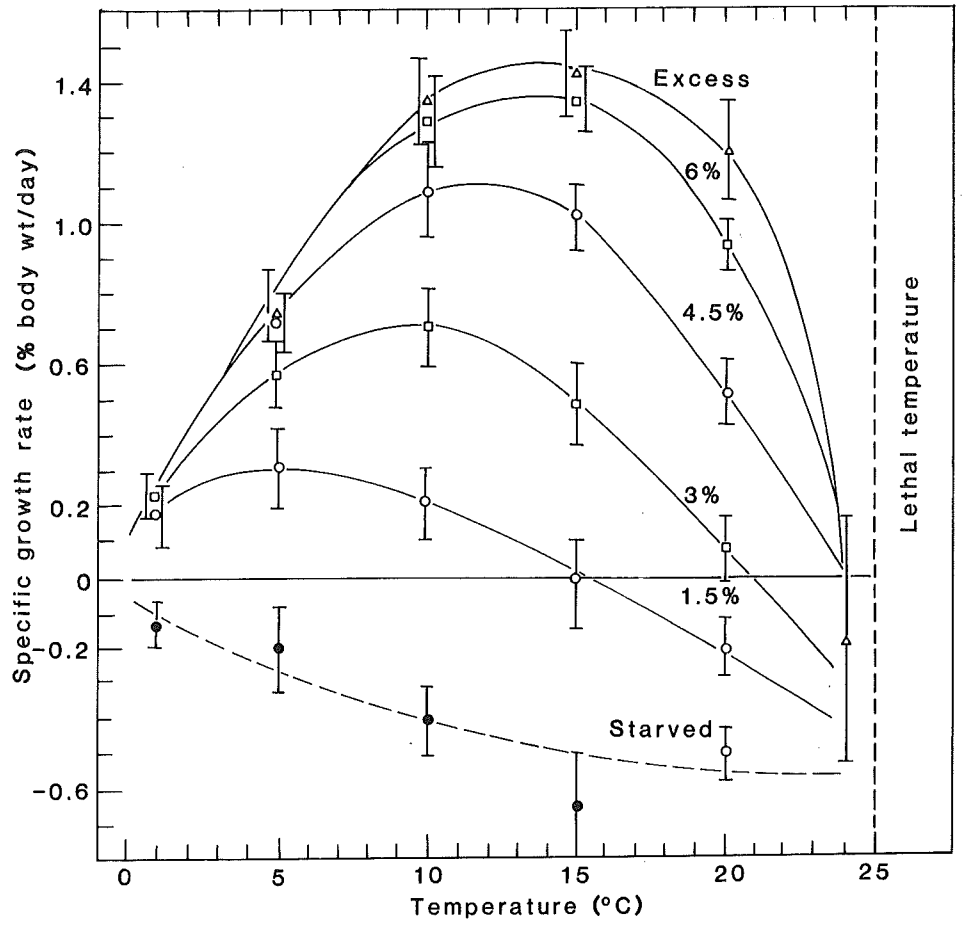

Figure 5

Growth rates of sockeye salmon as a function of water temperature and feeding rates. Figure from Brett et al., 1969.

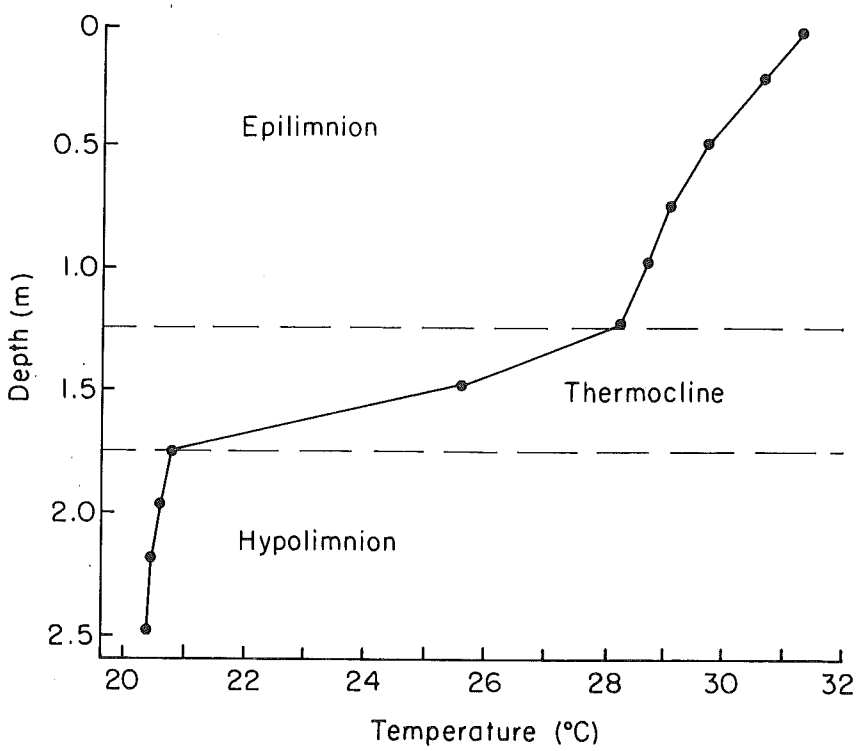

Figure 6

Thermal stratification in a fish pond. Figure from Boyd, 1979.

strong that continuous mixing greatly enhanced conditions for the fish.

SALINITY

Salinity is one of the major factors that determine the kind of fish that can be reared at a given location. Although some species like milkfish and mullet are euryhaline, most fishes tolerate a relatively narrow salinity range (Table 1).

Not only is it important to establish the salinity of a fish pond, but it is equally important to establish the salinity fluctuations that can occur. Some coastal ponds are subject to freshwater runoff, in which case salinities could vary from marine to freshwater. Some coastal ponds or ponds located in arid regions experience hypersaline conditions due to high evaporation rates and a low inflow of freshwater. Milkfish ponds on Christmas Island often exceed 150°/oo (Helfrich, pers. comm.), while Laguna Madre, Texas Lagoon, often has salinities in the range of 50 to 80°/oo (Pearse and Gunter 1957). Table 6 shows one classification of water based on salinity.

Potential salinity problems should be evaluated before siting a pond. If salinities are unsuitable for the fish species under consideration, then the pond should be sited elsewhere, a different culture species evaluated, or corrective measures sought. Corrective measures, if any are possible, typically include providing water with salinities needed to maintain the desired salinity. For example, this could mean a good freshwater source in a situation where high evaporation and hypersaline problems exist, or, conversely, diverting freshwater inflow and allowing marine-water influxes.

ALKALINITY, HARDNESS, AND pH

Alkalinity and pH conditions cause some of the most common water-quality problems. Usually the problem is with highly variable pH, and low alkalinity. The problem occurs in fresh or brackish waters.

Alkalinity is defined as the capacity of water to accept protons and it is measured by adding acid until a pH value of about 4.5 is reached. The acid combines with base substances such as carbonate, bicarbonate, and hydroxides. The amount of acid used is a measure of the total alkalinity.

Hardness tests were originally developed as an indicator of the water's capacity to precipitate soap. Hard water readily precipitates soap, thus creating a heavy scum and reducing the soap's cleansing capacity. Soap is usually precipitated by calcium and magnesium ions, but other polyvalent ions such as aluminum, iron, and manganese will also create hardness. Sodium and potassium ions do not contribute to the precipitation of soap. In most freshwaters, calcium and magnesium carbonates and bicarbonates predominate. In these

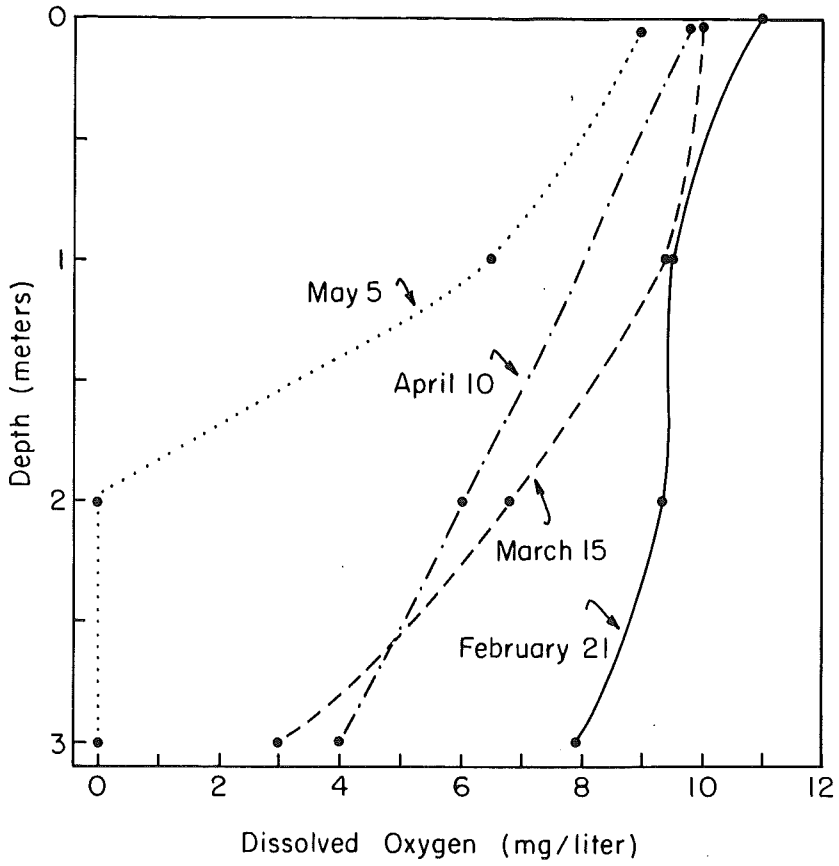

Figure 7

Oxygen depletion in a thermally stratified fish pond at Auburn, Alabama. Thermal stratification and high turbidity led to oxygen depletion below the 2 m depth. Figure from Boyd, 1979.

Table 6

A CLASSIFICATION OF WATER BASED ON SALINITY

Classification	Salinity, %
Fresh water	< 0.5
Oligohaline	0.5 - 3.0
Mesohaline	3.0 - 16.5
Polyhaline	16.5 - 30.0
Marine	30.0 - 40.0
Brines or Hypersaline	> 40.0

[a] Based on Hedgpath, 1957

waters, hardness and alkalinity are nearly the same. However, in waters with high concentrations of sodium carbonate alkalinity would be much greater than hardness. Conversely, waters with high concentrations of calcium sulfate could have much greater hardness than alkalinity. Of these two parameters, alkalinity is usually the more important for fish culture. However, because these values are usually very similar, alkalinity and hardness are often used synonymously. They are both relatively easy to measure, but hardness may be somewhat easier to determine.

The hydrogen ion concentration (pH) of water is a measure of the water's acid/base condition. It ranges from pH = 0 (extreme acidic), to pH = 7 (neutral), to pH = 14 (extreme basic). The toxicity of many substances, such as ammonia and hydrogen sulfide, are greatly influenced by pH. The pH of most freshwaters ranges between 6 and 9, which is an adequate range for most fishes. Values below pH 6 are generally deleterious to fish, and pH 4.5 to 5.0 is the lower limit of fish survival. Likewise, values above 9 to 10 are usually lethal. The most desirable range for fish is from pH 7 to 8, with minimum variation. Waters with a high capacity to resist changes upon the addition of acids or bases are said to be well buffered. Waters with high alkalinities are generally well buffered. Ocean waters have a very

high buffering capacity and a stable pH in the range of 7.8 to 8.3 (Sverdrup et al. 1942).

Low-alkalinity waters are usually unproductive (see fertilization section). They have low nutrient concentrations, little plant growth, large variations in pH, and low fish yields (Schaeperclaus 1933, Hickling 1962, Boyd 1979). Schaeperclaus was one of the first to classify the productivity of pond waters based on their alkalinity (Table 7). Although Schaeperclaus felt that optimal productivity occurred at alkalinities of 100 mg/l as $CaCO_3$ or greater in Germany, Boyd (1979) found that alkalinities of 25 to 30 mg/l as $CaCO_3$ (corresponds to total hardness of about 20 mg/l as $CaCO_3$) provided optimal fish production in the U.S. southeast. Boyd states that "lime applications (to increase alkalinity) may not be worth the bother and expense in waters containing slightly less than 20 mg/liter total hardness."

mechanisms. The lime increases the sediment pH and thus reduces the capacity of the sediments to bind plant nutrients like phosphorus (Ohle 1938, Bowling 1962). This not only releases these nutrients to the water where the phytoplankton can use them but also make added nutrients more available for plant growth. Higher sediment pH may also create more favorable conditions for microbial growth and thus lead to a more efficient detrital food chain and the increased production of benthic fish-food organisms (Pamatmat 1960). Arce (1974) observed an average pH increase from 5.2 to 6.8 in five limed Alabama ponds, while five unlimed (control) ponds had average pH values of 5.4 and 5.5 during the same period. Liming also increases the available carbon dioxide for photosynthesis (Arce and Boyd 1975), creates a more desirable water pH range, and buffers against drastic daily pH changes.

Table 7

POND PRODUCTIVITY RELATED TO TOTAL ALKALINITY[a]

Alkalinity, mg $CaCO_3$/l	Significance in pond culture
Zero	Water strongly acid, unusable for hatchery purposes, adding lime to the water unprofitable in most cases.
5 to 25	Alkalinity very low. Danger of fish dying, pH variable, carbon dioxide supply poor, water not very productive.
25 to 100	pH variable, carbon dioxide supply medium, productivity medium.
100 to 250	pH varies only between narrow limits, carbon dioxide supply and productivity optimal.
>250	Rarely found. pH very constant, productivity alleged to decline but not proven so far. Health of fish not endangered.

[a] Data modified from Schaeperclaus, 1933

Liming of ponds with low-alkalinity water and acid sediments to increase fish production is a well-established water-quality management practice (Schaeperclaus 1933, Ness 1946, Huet 1970). Hickling (1962) reported increased Tilapia production of 243 to 385 kg/ha through the application of 2,200 kg/ha of limestone and inorganic fertilizer. Arce and Boyd (1975) increased Tilapia production by about 25% in Alabama ponds limed at 3,836 to 4,371 kg/ha. Other researchers and aquaculturists have experienced similar results.

Liming and the corresponding increases in alkalinity cause increased fish production by several

Lime is commonly available as powdered limestone ($CaCO_3$, $Mg\ CO_3$) hydrated or slaked lime ($Ca(OH)_2$) or quick lime or unslaked lime (CaO). It is applied to the pond water or bottom. The preferred procedure is to apply the lime to the soil after the pond has been drained and dried, although liming is often done without draining the water.

Liming application rates vary greatly from pond to pond and from region to region. Boyd (1979) developed and described a simplified procedure for estimating liming rates for most Alabama ponds. His procedure involves measuring sediment (mud) pH before and after the application of a p-nitrophenol

buffer solution. Recommended lime application rates ranged from 91 to 7056 kg/ha of $CaCo_3$ (Table 8).

Using Boyd's techniques, alkalinity increased from about 17 mg/l to more than 30 mg/l in five Alabama ponds (Fig. 8). Hardness increased from about 10 mg/l to more than 25 mg/l. Alkalinity was typically 5 to 10 mg/l greater than hardness in these ponds, presumably due to nonalkaline earth carbonates.

DEWATERING AND DRYING

It is highly desirable, if not essential, to be able to fully drain a fish pond. Draining allows for the complete harvest of the fish crop, but that is not the only purpose for draining a fish pond. Reasons for dewatering and drying fish ponds include (Hickling 1962, Huet 1971):

Table 8

ESTIMATED LIME REQUIREMENTS IN kg/ha NEEDED TO INCREASE THE TOTAL HARDNESS AND ALKALINITY TO 20 mg/l OR GREATER[a,b]

Mud pH in water	Calcium carbonate required according to mud pH in buffered solution									
	7.9	7.8	7.7	7.6	7.5	7.4	7.3	7.2	7.1	7.0
5.7	91	182	272	363	454	544	635	726	817	908
5.6	126	252	378	504	630	756	882	1,008	1,134	1,260
5.5	202	404	604	806	1,008	1,210	1,411	1,612	1,814	2,016
5.4	290	580	869	1,160	1,449	1,738	2,029	2,318	2,608	2,898
5.3	340	680	1,021	1,360	1,701	2,042	2,381	2,722	3,062	3,402
5.2	391	782	1,172	1,562	1,548	2,344	2,734	3,124	3,515	3,906
5.1	441	882	1,323	1,765	2,205	2,646	3,087	3,528	3,969	4,410
5.0	504	1,008	1,512	2,016	2,520	3,024	3,528	4,032	4,536	5,040
4.9	656	1,310	1,966	2,620	3,276	3,932	4,586	5,242	5,980	6,552
4.8	672	1,344	2,016	2,688	3,360	4,032	4,704	5,390	6,048	6,720
4.7	706	1,412	2,116	2,822	3,528	4,234	4,940	5,644	6,350	7,056

[a] Table from Boyd, 1979

[b] The lime required (as calcium carbonate) is estimated from the pH of the pond muds before and after the addition of a buffer solution.

Liming typically causes a marked increase in alkalinity and pH immediately after the lime application. This is often followed by a reduction in alkalinity and pH and a leveling off of these values (Fig. 9). If a suitable amount of lime is applied and if water flushing rates are not excessive the benefits from liming should last several years. High flushing rates, however (e.g. Grier's Pond, Fig. 9), can nullify the lime applications since the lime is rapidly flushed from the pond. Boyd (1979) found that an annual lime application of 25% the initial dose was adequate to maintain high fish productivity in Alabama fish ponds with limited flushing rates.

The above procedures for estimating lime application rates do not apply to acid sulfide soils. These ponds often have a sediment pH of 4.5 or less, high dissolved-metal content, and are often unsuitable for fish culture even with intensive treatment. Boyd (1979) recommends a procedure for estimating the lime requirements of these soils, but cautions that "the efficacy of the procedure in estimating the lime requirement of pond muds with acid sulfide problems has not been evaluated."

1. Nutrient Regeneration. The drying of pond soils causes an accelerated rate of organic matter mineralization. This aerobic process results in mineral forms that are more readily released to the water when the pond is refilled. These nutrients increase plant growth and, consequently, fish production.

2. Fish Population Control. Periodic dewatering allows good control of fish populations. Fish can be sorted and restocked at densities that will maximize the production of desirable-sized fish. Stunting and the excessive production of small fish can be avoided by sorting and thinning the fish stock. Undesirable fish species can be removed.

3. Reduce Oxygen Demand of Sediments. Ponds with large amounts of organic matter develop anaerobic bottom conditions and the decomposition of the organic matter is slowed. Dewatering and drying accelerates the aerobic oxidation and decomposition of this organic matter. This creates a better pond sediment substrate for benthic fauna

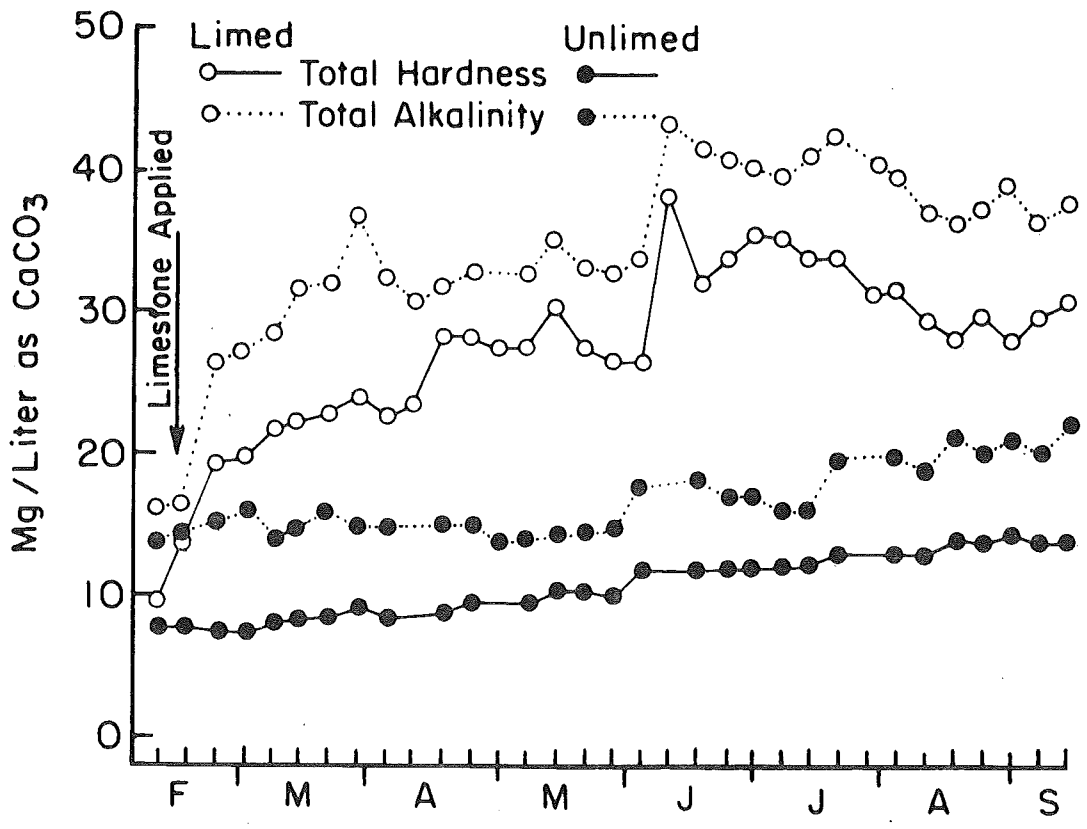

Figure 8

Total hardness and total alkalinity in limed and un-limed fish ponds. Figure from Boyd, 1979, after Arce and Boyd, 1975.

production and reduces the oxygen demand of the sediments when the pond is refilled.

4. Oxidation and Leaching of Acid Sulfate Soils. Dewatering and drying enhances the oxidation of sulfur in acid sulfate soils. The resultant acids can then be leached from the soil and the soil can be limed to create a favorable pH for fish culture (Singh 1980).

5. Control Vegetation. Vegetation can be controlled through dewatering and drying. If the vegetation also dries it can be burned to remove the aboveground growth, and the roots can be plowed or disked under. If the vegetation does not dry sufficiently it may be plowed under or used as cattle fodder. Some plants are controlled by prolonged dessication.

6. Disease Control. Certain fish and human diseases are difficult to control in water-filled ponds (see diseases chapter). Malaria mosquitoes are a particular problem in weed-choked ponds. Routine drying helps control the weeds and allows larvivorous fish (such as Gambusia) to control the mosquitoes when the ponds are refilled. The Schistosoma disease (Bilharzia) has its intermediate stage in snails and its primary stage in the blood of man. The snail is effectively controlled by periodic drying and liming of the soil. This also helps control weed growth, thus reducing the habitat available to the snail upon refilling. Stocking herbivorous fish further reduces weed growth and makes the snail more vulnerable to predation by carnivorous fish.

   Two fish parasites, the fish louse Argulus and the parasitic copepod Lernaea, can be controlled by periodic dewatering and drying. Lime application during the dry period greatly enhances treatment of these and other parasites.

7. Pond Maintenance. Dewatering and drying simplifies pond maintenance. Excess accumulations of sediment and debris can easily be removed by earthmoving equipment or by hand. This sediment is often a valuable addition to fields and gardens since it has a high nutrient content and good soil-conditioning properties. While they are dry, pond drainage channels and sluice boxes can be cleaned and restored. Fertilizers and lime can be

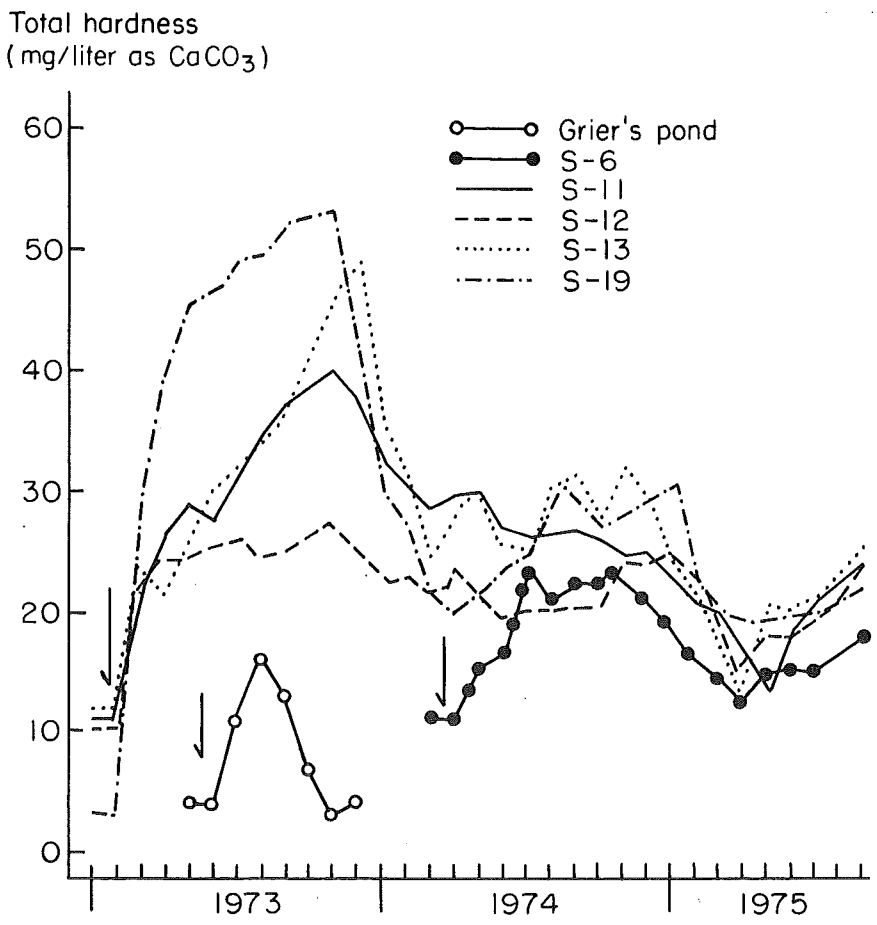

Figure 9

Long term effects of liming on six Alabama ponds. Grier's Pond had the highest water flow-through rate (3 weeks) and showed the least benefit from liming. The arrows indicate lime applications. Figure from Boyd, 1979, after Boyd, 1976.

added to the pond soil and disked in more easily when it is dry.

8. Crop Rotation. Often, crops such as rice, cotton, clover (and other legumes), or cereals are alternated with fish crops. These crops tend to increase the productivity of the fish crops, probably by (a) enhancing soil oxidation and thus making mineral nutrients more available when the pond is reflooded, by (b) producing organic material that promotes the growth of fish food organisms, and/or by (c) fixing atmospheric nitrogen, which is released to the water upon reflooding.

When to dewater and dry, and for how long? There are no good rules for the frequency or duration of dewatering and drying. In cold climates, the common practice is to dewater and dry each winter, at least in the shallow pond. The fish are either harvested in the fall or moved to deeper overwintering ponds that are less subject to oxygen depletion and fish kills. Fish are less stressed by handling during cold periods. They have greatly reduced metabolic and food requirements during the winter and do not grow much. In China, a pond may be drained every one to two years (Hoffman 1934), while in Germany the practice was to rear fish for three years and then to grow dry land crops for three years (Wunder 1949). The latter program is probably excessive.

The appropriate frequency and duration of drying will largely depend on the nature of the pond soils, the climate, the vegetation in the pond, and other relevant factors. The appropriate period could be as short as a few days or as long as a year or more. Ponds with soils and construction that facilitate rapid dewatering, with a warm, dry climate, an with a minimum of vegetation cover may require only a few days of drying (Hickling 1962). However, ponds soils that remain wet may not benefit greatly from much longer periods of "dewatering" and "drying."

TURBIDITY

Pond turbidity is caused by organic matter like phytoplankton and by suspended organic matter like silt and clay. Inorganic turbidity can be most troublesome since it can reduce the light penetration required for photosynthesis and thus reduce oxygen generation and phytoplankton production. Inorganic turbidity may also reduce the benefits of artificial fertilization since phosphorus may absorb or adsorb on the sediment particles.

Persistent inorganic tubidity is often caused by negatively charged colloidal clay particles. They stay dispersed and in suspension due to their small size and electrical charge. In these cases, turbidity may be reduced by applying organic materials such as cut hay or manure to the ponds (Irwin and Stevenson 1951, Swingle and Smith 1947). Decomposition of these organic materials leads to increased CO_2 concentrations, decreased pH, and precipitation of the clay. Irwin and Stevenson recommend hay applications of 0.05 kg/m^3 of pond water with 25 mg/l turbidity and 0.4 kg/m^3 for 200 mg/l turbidity. Swingle and Smith recommended 2 or 3 applications of barnyard manure at the rate of 2,440 kg/ha.

Boyd (1979) tested alum (aluminum sulfate), gypsum ($CaSo_4 \cdot 2H_2O$), and unslaked lime ($Ca(OH_2)$) on several soils types. He found alum to be the most effective. In six test ponds an average alum application of 20 mg/l resulted in an average turbidity decrease of 91%. In one pond, turbidity decreased from 830 mg/l before treatment with 20 mg/l of alum to 24 mg/l after treatment (97% reduction). Alum is relatively nontoxic to fish and other aquatic organisms, although it can cause a substantial drop in water pH.

DOMESTIC WASTES

Domestic wastes contain high concentrations of valuable nutrient materials, but they also contain potentially high concentrations of human pathogens. These wastes have been used for many centuries for both agricultural and aquaculture purposes. However, the threat of disease is ever present when domestic waste is used to culture food products for human consumption. The threat is particularly acute for species that are sometimes eaten raw (such as oysters or mussels) or for species that are sometimes pickled or not thoroughly cooked.

The United States has strict laws regarding water quality standards for shellfish-rearing areas, but infectious diseases (e.g. hepatitis) still are attributed to these sources. There are also strict laws regarding the use of domestic wastes for fish culture in the United States. Although there is much interest in the possible use of these waste waters for aquaculture (Devik 1976), it is unlikely that we will see large scale uses in the United States in the foreseeable future.

The use of domestic or agriculture wastes for aquaculture is an established practice in much of the world. It is relatively safe, providing precautions are taken to assure that the end-product is properly handled and cooked before consumption.

AGRICULTURAL POLLUTION

The careless use of pesticides and herbicides is probably agriculture's greatest threat to aquaculture. These toxicants may drift into fishponds as overspray from agricultural fields or may concentrate in water sources that drain the treated area. In addition, some pesticides and herbicides may contaminate the soil, so that rotating field crops with aquacultural crops may cause excessive contamination of the fish.

As with industrial wastes, the best approach is to site the aquacultural operation away from sources of potential agricultural pollution. Steps should be taken to alert the crop farmer to the damage he can cause the fish farmer through careless use of his chemicals.

In addition to agricultural toxicants, misused fertilizers, runoff from animal feed lots, and excessive erosion are other potential threats posed by agriculture to fish culturists. Fertilizers and animal wastes can be directly toxic, especially if ammonia concentrations and water pH values are high. These materials can also lead to excessive nutrient concentrations in the fish pond, excessive plant growth, and ultimately oxygen depletion. Erosion carries silt, sand, and other materials into ponds where they settle and lead to a filling in of the pond. This shortens the useful life of the pond, creates problems with macrophytes, reduces the productive volume, sometimes increased turbidity (and thus reduces phytoplankton growth), and reduces fish production.

INDUSTRIAL WASTES

There are a large number of industrial wastes that are potentially harmful to aquaculture. A recital of these wastes is unnecessary, and indeed beyond the scope of this review. They are, however, of paramount importance to the aquaculturists. Great care should be exercised when siting an aquaculture operation to avoid contamination from this source. Precautions must also be taken by industrial concerns to avoid contaminating established aquaculture operations with their discharges. Liability for damages that result from such discharges will almost always lie with the discharger.

AQUATIC PLANTS

Macrophytes

Macrophytes are large aquatic plants that are either rooted to the bottom or have connection with the bottom or some other stable substrate. The aquatic plants that cause problems for pond aquaculturists may be classified as follows:

1. Riparian, or shore, plants are plants that grow at or above the water's edge. They may be woody or soft stemmed (e.g. willow).

2. Emergent plants are those plants that are found below water, usually rooted to the bottom, and have substantial portions of the plant extending above the water's surface (e.g. cattails, rushes).

3. Submergent plants are those plants that are totally, or nearly always, underwater. They typically lack woody parts, and they may be rooted or not (e.g. Elodea, Potamogeton and filamentous algae).

4. Floating plants, where most of the plant grows on the water's surface (e.g. water hyacinth, water lilies, duckweed).

Proper identification of a nuisance macrophyte is usually necessary before it can be properly dealt with. This is especially true for chemical control methods, since many macrophyte toxins are specific for certain plants. Dosage rate and application methods may also vary for different plants. There are a number of useful publications for identifying aquatic plants, including Fossett (1960), Weldon et al. (1969), Klussman and Lowman (1975), and Applied Biochemists (1979).

Aquatic macrophytes may seriously impact fish ponds if they become excessively abundant. Excessive macrophyte growth may: tie-up nutrients and biomass that could be more efficiently used by the fish through the phytoplankton foodweb; greatly restrict phytoplankton production; provide abundant shelter for small fishes and thus lead to their overabundance and stunting; greatly hinder harvest of the fish crop; restrict water circulation; contribute to accelerated sedimentation of the pond; restrict movement and living space for the fish; and contribute to oxygen depletion and fish kills when the plants die (Hickling 1962, Huet 1970, Stickney 1979). These problems can range from the minor to the very serious. In the latter case, fish production is often greatly reduced and the rearing operation becomes uneconomical. The amount of tolerable macrophyte cover is not easy to define, but Boyd (1979) suggests that 10 to 20% cover of the pond is the upper limit.

Troublesome macrophytes may quickly fill in or "incapacitate" a pond, but they produce relatively low standing crops (Forsberg 1960, Westlake 1975, Boyd 1975). Although they may be used for animal feed or mulch, their value is minimal. Furthermore, very few fresh water macrophytes are of any value to humans. The more prominent ones are water spinach (Ipomea), watercress (Nasturtium), arrowhead (Sagittaria), wild rice (Zizania), and cattails (Typha) (Bardach et al. 1972). Except for watercress, there is little interest in culturing these plants for human consumption and, with the exception of the cattails, they seldom cause serious problems in fish ponds.

Macrophytes are a particular problem in shallow ponds where light can penetrate to the bottom during the early growing season. Macrophytic growth may progress at a rapid rate and deprive phytoplankton of the nutrients needed for their growth. Many macrophytes can draw nutrients from the sediments as well as from the water. This gives them an added advantage in their competition with phytoplankton. Deep ponds (greater than 1.5 m deep) with moderate to high turbidity seldom have a problem with macrophytes, except along their shorelines.

Macrophyte Control Methods

Mechanical Control

Macrophyte control by mechanical or biological means is ecologically the most desirable. As with any plant-control technique, mechanical control is best achieved before dense growth of the plants occurs. Younger plants not only have less biomass, but they are often easier to cut (they are less fibrous) or detach.

Macrophytes may be cut by hand or machine. Hickling (1962) used handscythes and a motorized cutter on reeds, rushes, and sedges in Malaysia with good success. He obtained the best results when the plants were first cut early in the season and then once or twice later on. The regrowth of the plants exhausted their stored root reserves and led to longer-term control. His success was greatest in water of 1 m depth or deeper, expecially when phytoplankton growth resulted in greater turbidity following the cuttings.

After mechanical cutting of the macrophytes, the cut weeds should be removed from the water to prevent oxygen depletion and excessive filling of the pond. Huet (1970) recommends that not more than 1,500 kg/ha of weeds remain.

A properly constructed pond is one of the best mechanical means of controlling plant growth. This usually means a minimum depth of 1 to 1.5 meters and relatively steep slopes near shore. The slope should not exceed 4:1 for safety reasons (Glenn, pers. comm.). A pond of this design will greatly reduce the potential for macrophyte growth since it creates favorable conditions for phytoplankton growth and for the shading of the bottom areas.

Many aquatic plants can be effectively controlled by periodic drying of the pond. Drying and mowing, drying and burning, and drying and disking are effective (Hickling 1962).

Biological Control

Biological control often results in both effective control of nuisance macrophytes and increased fish production.

Biological control of macrophytes through the enhancement of phytoplankton is probably the most popular technique employed. Macrophytes are generally sparse or absent from ponds with moderate to heavy plankton blooms and water depths of 1.5 m or greater. Phytoplankton turbidity or inorganic turbidity effectively reduce light penetration to the pond bottom and thus limit macrophyte growth. Hutchinson (1975) found that macrophytes did not grow below 1.5 m when Secchi disc transparencies were 1 m, nor below 2.5 m when the Secchi disc depth was 2 m. Boyd (1975) found similar results and suggested that macrophytes could not grow at depths greater than twice the Secchi disc transparancy. Since Secchi disc depths of about 0.5 are generally considered optimal for phytoplankton densities, it follows that not much macrophyte growth will occur below the 1.5 m depth.

Herbivorous animals such as grass carp, tilapia, ducks, geese, swans, cattle, and nutria, are often used to control macrophyte growth (Hickling 1962, Huet

1970). Cattle, nutria, and the birds are most effective in controlling plants in shallow water and on the pond bank. Not only can they be very effective control measures, but they also contribute manure and nutrients to the pond and provide an additional protein crop for market. Grass carp and tilapia are particularly valued fish crop. However, they are less successful in areas with cool climates and their importation in some areas is also restricted.

The common, or Israeli, carp is sometimes used for weed control (Huet 1970). Although it derives some nutrition from the vegetation, it mainly controls the weeds by dislodging them through its "rutting" action on the pond bottom. It also increases the water turbidity and thus helps reduce light penetration to the pond bottom. The disadvantage of the common carp is that large numbers are often required for effective control (2,500 to 3,000/ha; Huet 1970). They also increase inorganic turbidity (thus reducing phytoplankton growth) and are not as desirable a market fish as certain other species.

Chemical Control

Chemical control of macrophytes is often very cheap and effective. However, it can upset the ecological balances in a fish pond and cause reduced production (or death) of the fish and their forage organisms. Herbicides may be directly toxic to fish and their food organisms, or they may cause oxygen depletion through decomposition of the dead macrophytes.

Although there are a large number of herbicides, only a few are approved in the United States for use in food fish ponds. Meyer et al. (1976) list only copper sulfate, 2,4-D, Diquat dibromide, endothall, and simazine. in the United States these chemicals can only be sold to those persons licensed to apply them.

Boyd (1979) cautions that "in pond fish culture, herbicides should be used only to eliminate aquatic vegetation so that plankton blooms may develop." He further states that "unless a plankton bloom is encouraged, macrophytes will simply regrow as soon as herbicide treatments return to nontoxic levels."

There is sometimes no suitable alternative to chemical treatment. In these cases application should be made as directed by the manufacturer and the results closely monitored.

Phytoplankton Phytoplanktons are small, usually microscopic plants that are carried about by water currents. They give the water its green appearance and they are an important link in the food web. Through photosynthesis they convert solar energy and inorganic compounds into organic compounds. In this process they also produce oxygen, which dissolves in the water and helps maintain aerobic conditions.

Excess fertilization may cause phytoplankton growth to become excessive or undesirable forms of phytoplankton to develop. This can lead to oxygen depletions or off-flavors in the fish flesh through the production of geosmin by the algae (Lovell and Sackey 1973).

Phytoplankton Control Method Sometimes it is easier to treat consequences of excessive phytoplankton growth than to treat the phytoplankton directly. This is treating the symptom rather than the cause, but it is often as effective and more practical. The usual symptom is oxygen depletion, which is discussed earlier in this chapter.

Long-term treatment usually requires some reduction of nutrient inputs. This is most easily achieved when the principal inputs are applied by the pond operator; reduction of nutrient inputs is more difficult when they are from watershed runoff or groundwater inflows.

Flushing clean water throught the pond is one means of reducing nutrient and phytoplankton populations. Water can be exchanged between ponds or washed downstream. However, the latter remedy may require large amounts of source water.

Biological control of phytoplankton has not been thoroughly evaluated. Some results indicate that plankton-eating fishes will stimulate phytoplankton growth rather than retard it (Hurlbert et al. 1972, Perschbacher 1975). Primary production was 5.0 mg O_2/l/day in ponds with planktivorous fish, vs 3.5 mg O_2/l/day in ponds without such fish. Likewise, phytoplankton density was 7,500 cells/ml in the fish ponds, vs 3,100 cells/ml in the ponds without the fish. Malea (1976) and Boyd (1979) found that although phytoplankton densities may not be decreased by a polyculture program using planktivorous fish, the total fish production was substantially increased. In addition, there could be a change in the types of algae produced in these systems even though total algal density is not decreased. For example, if blue-green algae (which produce geosmin and often are associated with oxygen depletion) could be replaced by green algae or diatoms, there could be a net improvement in water quality even though the total algal biomass is the same. There has not yet been sufficient investigation of this management technique to assess its efficacy.

Copper sulfate is the common algacide used. It is usually broadcast into the water as a crystal or dissolved in the water by various means. More recently, its chelated form (with citric acid) has become popular. Simazine has also become popular recently for controlling both phytoplankton and certain macrophytes. Although both chemicals are very effective algacides, they can reduce both fish production and dissolved oxygen concentrations (Boyd 1979). Tucker and Boyd (1978) observed a substantial reduction in dissolved oxygen (and phytoplankton density) in a fed catfish pond which was treated with simazine (Figs. 10 and 11). The oxygen depression persisted all summer.

Copper sulfate may be a useful means of controlling scum-forming blue-green algae (Kessler 1960, Crance 1963). However, special care should be exercised not to cause toxicity to the fish or cause excessive oxygen depletion.

Boyd (1979) concluded that "the use of algacides to limit phytoplankton growth in ponds used for intensive fish culture is analogous to a human losing weight by taking periodic, sublethal doses of a toxin instead of reducing his food intake."

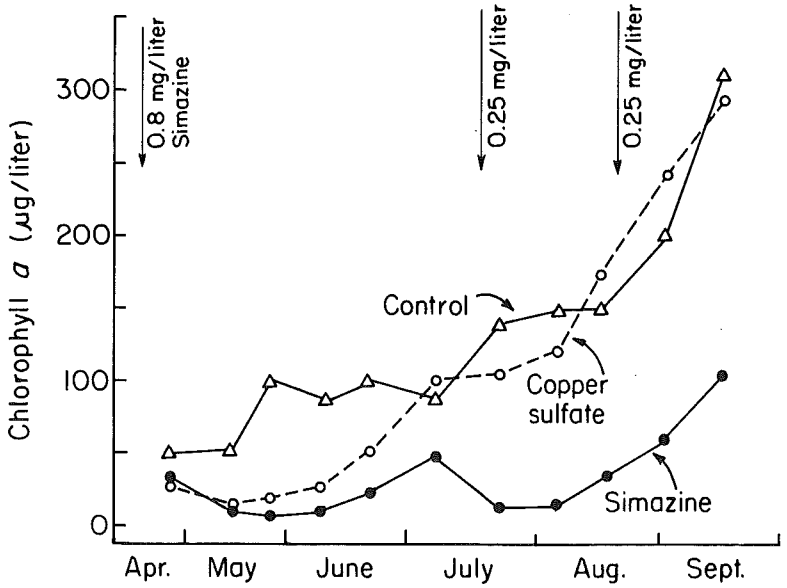

Figure 10

Effects of copper sulfate and simazine on chlorophyll a concentrations in fish ponds. The dates when the algacides were added are shown by arrows. Figure from Boyd, 1979, after Boyd, 1978.

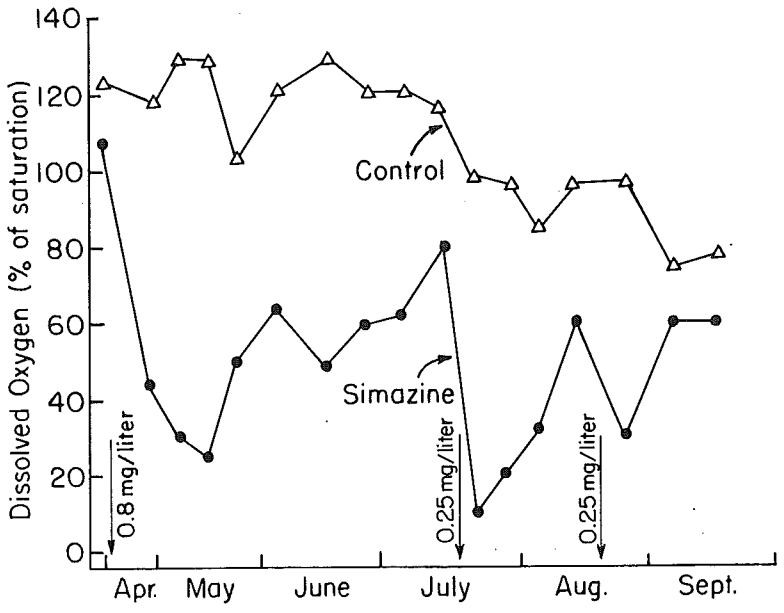

Figure 11

Effects of simazine on dissolved oxygen concentrations in fish ponds. The dates when the algacide was added are shown by arrows. Figure from Boyd, 1979, after Tucker and Boyd, 1978.

SELECTED FUTURE RESEARCH NEEDS

1. Thermal and Chemical Stratification. The effects of thermal stratification and oxygen depletion on the bottom waters should be further evaluated. In particular, the production of benthic fauna forage organism, depth distribution and feeding habits of the fish, zooplankton depth distribution, and nutrient cycling should be studied.

Even shallow ponds of 1.5 to 2.0 meters depth may stratify periodically, while deeper ponds may have long periods of stratification. These conditions could cause a reduction in forage production and the availability of forage to the fish, and consequently a reduction in fish production.

The research design should include a variety of ponds, including shallow ponds with ephemeral stratification and deep ponds with sustained periods of stratification.

2. Continuous Circulation. In connection with the above, the effects of continuous circulation by artificial means should be evaluated. Preliminary research results indicates that continuous circulation/aeration can result in a substantial increase in fish production and increased DO. However, the mechanism whereby this occurs is not known

3. Emergency Aeration. Partial aeration of a fish pond using a semi-permeable barrier should be evaluated and compared with aeration of the entire pond. In particular, the energy requirements, rate of oxygen increase, and movements of fish into the aerated zone should be studied.

4. Liming Procedures. Liming procedures should be developed and tested for a variety of soil types and regions. The methods developed by Boyd (1979) for certain Alabama soils are most useful, but their widespread application is untested. Possibly these techniques, with modifications, could be developed for general use.

5. Acid Soil Restoration. Some acid soils are not readily restored by existing reclamation practices. Alternative methods of restoring these soils should be evaluated.

6. Phytoplankton Manipulations. Although phytoplankton population densities are often at desirable levels, the species composition may not be optimal. Conditions favoring high phytoplankton production also tend to favor the growth of blue-green algae or other forms that are not preferred foods of many herbivores. It may be possible to artificially manipulate the species composition of phytoplankton by the use of selective algacides, nutrient additions, herbivorous fish, or artificial circulation.

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POND PRODUCTION SYSTEMS: DISEASES, COMPETITORS, PESTS, PREDATORS, AND PUBLIC HEALTH CONSIDERATIONS

by

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INTRODUCTION

Production losses in warmwater fish pond culture can result from the occurrence of disease, competitors, pests, or predators in these systems. Reductions in yields are manifest by growth suppression and/or actual fish morbidity and mortality. It is not possible with the presently available data base to directly assess the economic impact of disease, competitors, pests, and predators on warmwater aquaculture production. This is primarily due to the lack of morbidity and mortality records in fish-raising industries. Klontz (1972) pointed out that in the U.S. livestock industry mortality due to disease rarely exceeds 0.5 - 1% per year, and he predicted that the annual mortality in fish culture settings exceeds 1%. The sporadic information available suggests that a mortality rate of 5 - 20% or greater is currently experienced in some warmwater pond culture systems. Without a doubt, survival rates and, therefore, production levels in warmwater pond aquaculture systems can be greatly improved. Understanding the diseases in these fish should result in improved survival and production yields.

This section briefly reviews the diseases (infectious and noninfectious), competitors, pests, and predators currently known to affect the following warmwater pond cultured fish species: channel catfish (Ictalurus punctatus), common carp (Cyprinus carpio), grass carp (Ctenopharyngodon idellus), silver carp (Hypophthalmichthys molitrix), bighead carp (Aristichys nobilis), Indian carp (Catla catla), the tilapias (Tilapia spp. and Sarotherodon spp.), Clarias spp., mullet (Mugil spp.), and milkfish (Chanos chanos). For the diseases discussed, the information provided is largely limited to the epidemiology and control. Specific information regarding diagnostic procedures, pathology, etc., can be found in the textbook Fish Pathology, edited by Ronald J. Roberts, or other references included in the bibliography. A discussion of the public health considerations in warmwater pond aquaculture is also included in this section.

INFECTIOUS DISEASES

Diseases of Viral Etiology

Viruses are obligate, intracellular organisms many of which are known to cause disease in host species. Wolf and Mann (1980) list 32 viruses that have been isolated from or are known to occur in fish. Six of these viruses are known to cause disease in such sub-temperate and tropical freshwater pond fish species as common carp (Cyprinus carpio), grass carp (Ctenopharyngodon idellus), tilapia (Sarotherodon and Tilapia spp.), and channel catfish (Ictalurus punctatus). Viruses have not been reported from mullet (Mugil spp.), milkfish (Chanos chanos), silver carp (Hypophthalmichthys molitrix), big head carp (Aristichtys nobilis), mud carp (Cirrhinus molitorella), catfish (Clarias sp.), or the Indian carp (Catla catla).

Control methods for viral diseases in fish are limited to quarantine and restriction of movement, test and slaughter, sanitation and disinfection, reduction of environmental stressors, and good nutrition. Vaccines are presently not available on a commercial scale nor are there chemoterapeutic agents for treatment. Secondary bacterial infections may be dealt with using appropriate antibiotics.

Channel Catfish Virus Disease (CCVD)

Channel catfish virus (CCV) is a herpes virus that causes a systemic disease in fry and fingerling channel catfish at water temperatures of 25-30°C. This disease can be catastrophic (mortality approaching 100%) in susceptible channel catfish populations when environmental conditions favor the spread of the virus. This disease is a serious threat to channel catfish culture (Plumb, 1978).

The distribution of CCV is thought to be limited to the United States, although an isolated case of CCVD was reported in a batch of fry shipped to Central America from the United States (Plumb, 1978). Reducing the temperature from 28 to 18°C has been found to reduce CCVD mortality from 95 to 24% (Plumb, 1978). The best method of control is avoidance of infected stocks (Plumb, 1978).

Carp Pox

Carp pox is a relatively common benign cutaneous proliferative disease of cyprinids. It has been recognized as a disease of cultivated common carp (Cyprinus carpio) for more than 400 years (Liversidge and Munro, 1978). The etiologic agent has been tentatively identified as a herpes virus. Carp

pox only rarely causes mortality in carp but the cutaneous growths may reduce the value of the fish for aesthetic reasons. Carp pox is known to occur in Europe, but its geographical distribution is probably more extensive. Prevention is through destruction of infected stocks, and restriction of movement of potential carriers.

Lymphocystis

Lymphocystis is a benign cutaneous proliferative disease of many fresh and marine fish species. Lymphocystis is caused by an iridovirus. The occurrence of this disease in fish populations is sporadic. Infection of fish by this virus results in chronic verrucose lesions on the skin and fins. It is rarely fatal, but infected fish may be unsuitable for sale for aesthetic reasons. The virus is thought to be transmitted horizontally. Lymphocystis has been reported to occur in Europe, North and South America (Wolf, 1968), and Africa (Paperna, 1974, cited in Balarin and Hatton, 1979). Most species of fish are considered susceptible. Spontaneous recovery of infected fish commonly occurs. Prevention includes deriving stocks from fish populations free of lymphocystis and elimination of diseased individuals in cultivated populations.

Spring Viremia of Carp (SVC) and Swimbladder Inflammation (SBI)

SVC and SBI are systemic diseases of common carp (Cyprinus carpio) and possibly other cyprinids caused by Rhabdovirus carpio. SVC is probably synonymous with infectious dropsy of carp (Wolf, 1977; Bucke and Finlay, 1979). SVC is a highly contagious disease that causes extensive mortality in cultured carp populations. R. carpio is harbored in carrier fish and is horizontally transmitted to susceptible fish. Vertical transmission of R. carpio is considered probable (Ahne and Wolf, 1977). Grass carp (C. idellus) are susceptible to experimental infections with R. carpio (Wolf, 1977). R. carpio has only been positively identified in Europe, the Soviet Union (Ahne and Wolf, 1977), and Great Britian (Bucke and Finlay, 1979). Fijan (1972, cited in Ahne and Wolf, 1977) postulated that the virus is present wherever infectious dropsy of carp has been found. Bardach, Ryther, et al. (1972) mention infectious dropsy as a disease problem in Chinese carps. Prevention of SVC and SBI is through avoidance of infected carp stocks, quarantine, and restriction of movement of known infected fish. Control methods are limited to reduction of environmental stressors, good husbandry, and proper nutrition.

Grass Carp Rhabdovirus

Ahne (1975) reported the occurrence of infectious dropsy in grass carp (C. idellus) caused by a rhabdovirus (grass carp rhabdovirus). This virus has been shown to be similar but not identical to Rhabdovirus carpio). Instead, grass carp rhabdovirus is considered to be the same as pike fry rhabdovirus (Wolf and Mann, 1980). This virus has been reported in Holland and Germany, but the geographical distribution could be much greater. Horizontal and vertical transmission has been demonstrated (Liversidge and Munro, 1978). Prevention is through avoidance of infected carrier fish. Control methods are limited to reduction of environmental stressors, good husbandry, and proper nutrition.

Carp Gill Necrosis Virus

An iridovirus-like agent has been seen using electron microscopy in association with necrotic gill disease in common carp (Cyprinus carpio) (Wolf and Mann, 1979). Little is known about this virus and its potential as a primary etiologic agent in gill disease of carp.

Diseases of Bacterial Etiology

There are 18 recognized bacterial diseases of freshwater and marine fish species. Seven of these diseases are known to affect tropical pond aquaculture species. Lewis and Plumb (1979) state that bacteria are among the most important pathogens of cultured channel catfish. Carp raised in temperate climates are reported to suffer from Aeromonas sp. and Pseudomonas sp. infections. Haller (1974) and Scott (1977) cited in Balarin and Hatton, 1979) reported presumed bacterial disease outbreaks in tilapia cultured in Kenya. Sairg (1971) points out that bacterial diseases do not seem to be much of a problem in pond culture in subtropic regions (Israel) and Africa. Reports of diagnosed cases of bacterial disease in pond-cultured milkfish and mullet are nonexistent in the literature. Tilapia are susceptible to experimental infections with Aeromonas hydrophila and Aeromonas salmonicida (Almeida, Silva and Freitas, 1968).

Fin Erosion or Rot

Fin erosion and ulceration in cultured fish is widely accepted as being a disease complex caused by overcrowding or exposure to other environmental stressors, poor nutrition, and bacterial infection. The species of bacteria isolated from ulcerative lesions of the fins is variable but is usually a gram-negative bacteria in the genus Aeromonas or Pseudomonas. Prevention and control methods include good husbandry practices, proper nutrition, and sanitation. The application of antibacterial drugs in the feed or water may be useful in the treatment of fin rot, but primary emphasis should be placed on correcting husbandry practices and reduction of stressors.

Bacterial Septicemia

Bacterial septicemia is an acute to subacute systemic bacterial disease of fish caused by Aeromonas spp. (i.e., A. hydrophila) and Pseudomonas spp. All species of fish are regarded as susceptible (National Academy of Sciences, 1973). Outbreaks of bacterial septicemia can result in high mortalities in fish populations and frequently - if not always - follow exposure of fish to stressors such as low oxygen, handling, or transfer. Aeromonas spp. and Pseudomonas spp. are ubiquitous in aquatic environments. Preventative measures include good husbandry, sanitation, and proper nutrition. Bacterins are presently not available. Treatment with systemic antibacterials such as terramycin or sulfamerazine can be effective.

Columnaris Disease

Columnaris disease, usually a cutaneous but occasionally a systemic disease, is caused by Flexibacter columnaris. The gills and all cutaneous surfaces may be affected. Columnaris disease is widespread in young channel catfish (Ictalurus punctatus) and carp species. Most other freshwater fish species are

regarded as susceptible (Richards and Roberts, 1978). F. columnaris is a widely distributed saprophytic organism in aquatic environments (Richards and Roberts, 1978). Columnaris disease is most common in catfish culture when water temperature is greater than 20°C (Lewis and Plumb, 1979). Prevention of columnaris disease is through good husbandry and nutritional practices. Lewis and Plumb (1979) suggest potassium permanganate at 2-3 ppm in the pond water or terramycin at 83 gms per 100 lbs. of feed for 10 to 12 days, or Furacin at 150 gm per 100 lbs. of feed for 12 days. Valuable fish (broodstock) may be injected with terramycin (25 mg/lb) or Erythromycin (4 mg/lb). Reichenbach-Klinke (1973) suggests sulfamerazine (mixed into the feed 10-12 gm/liter:50 kg fish).

Mycobacteriosis

Mycobacteriosis is a chronic systemic disease of fish caused by Mycobacterium spp. Outbreaks of mycobacteriosis occur infrequently in cultured cyprinids (Snieszko, 1978). Mycobacteriosis has not been reported from pond-cultured mullet (Mugil sp.), milkfish (Chanos chanos), Clarias sp., Tilapia and Sarotherodo spp., or channel catfish (Ictalurus punctatus). Prevention is through avoidance of infection by quarantine and restriction of movement of infected fish and by the use of fish feeds which contain only sterilized fish flesh, rather than untreated fish products. Chemotherapeutics are not known to be effective for treatment of mycobacteriosis in fish. The species of mycobacterium which infect fish may infrequently cause skin infections in man. Mycobacteriosis has not been recognized as a problem in tropical pond aquaculture systems.

Edwardsiellosis

Infections caused by Edwardsiella tarda are reported in Ictalurids, Cyprinids, and Anguillidae in the southern United States and Southeast Asia. E. tarda infections cause gas-fill lesions in the muscles of mature catfish (Lewis and Plumb, 1979). Mortality in channel catfish cultured in ponds seldom exceeds 5%, but if fish are transferred to holding tanks losses may reach 50% (Lewis and Plumb, 1979). E. tarda is widespread in organically polluted waters (Richards and Roberts, 1978). Prevention is through reduction of environmental stressors, good husbandry, and proper nutrition. Treatment with antibacterials is reported to be effective. Terramycin, 83 gms per 100 lbs. feeds for 10 to 12 days (Lewis and Plumb, 1979), and Sulphonamide or Furacin (Richards and Roberts, 1978), are reported to be effective.

Diseases of Fungal Etiology

The National Academy of Sciences (1973) lists five major mycotic diseases that cause serious epidemics in cultured and wild fish and shellfish. Three of these disease are recognized as problems in tropical pond aquaculture species.

Branchiomycosis

Branchiomycosis, or mycotic gill rot, is a necrotic gill disease of common carp (Cyprinus carpio), channel catfish (I. punctatus), and many other fish species caused by Branchiomyces spp. Sairg (1971) states that in areas of Europe where this disease commonly occurs it is one of the greatest threats to commercial fish farming. Branchiomycosis has been reported in fish from Europe, Israel, the Balkan states, U.S.S.R., and the southern United States. This disease is most prevalent in ponds high in decaying organic matter (Sairg, 1971). Infection and morbidity rates of up to 50% may occur (Richards, 1978). In Israel, branchiomycosis occurs infrequently but causes high mortalities (Sairg, 1971). There is no known treatment for this disease. Control methods are limited to good sanitation and such management practices as increased water flow and prompt removal of dead fish.

Saprolegnosis and Achylosis

Saprolegnosis and achylosis are acute fungal diseases of fish and fish eggs caused by fungi in the genera Saprolegnia and Achlya. Saprolegnosis is by far the most commonly encountered. All species of tropical pond-culture fish species are considered susceptible. These diseases generally arise as cutaneous infections (skin or gills) following insults such as traumatic wounds, bacterial infections, or nutritional deficiencies, that cause disruption to the mucous layer. Once established, the fungus can spread to adjacent healthy tissues and may eventually result in death to the host. In fish-egg incubators Saprolegnia usually develops on detritus or dead eggs and rapidly spreads to healthy eggs, killing them (Rogers, 1979). Saprolegnia spp. and Achyla spp. are ubiquitous in natural waters. Preventative methods include good pond and hatchery practices and sanitation. Treatment of individually infected fish with malachite green (67 ppm dip for 10-30 sec.) has been reported as effective (Plumb, 1979). The treatment of ponds for saprolegnosis with 0.1 ppm malachite green or 2 ppm potassium permanganate is reported to be occasionally useful (Plumb, 1979).

Parasites

Approximately 100 genera of protozoan and metazoan parasites have been described as the etiologic agents of fish and shellfish diseases (National Academy of Sciences, 1973). Fortunately, only a handful of these parasitic organisms are of serious consequence to pond-culture fish. Sairg (1971) states that ectoparasites are the largest group of disease organisms in warm water fish ponds. The significant parasites in pond aquaculture include members from the Phyla Protozoa, Platyhelminthes, Aschelminthes, Arthropoda, and Annelidae.

Fish parasites can be grouped according to their usual location on the host. Ectoparasites are found on the external body surfaces, including the gills, and endoparasites locate in internal organs such as the liver, kidney, or intestines. According to Bauer (1961), parasites affect fish populations by causing: (1) mortality (1-100%); (2) reduction in growth; (3) weight loss, or (4) suppression of reproductive activity or efficiency. In addition to these effects, which can have an impact on fish production, the poor carcass quality of fish infested with parasites can result in reduction of market value for aesthetic reasons (Rogers, 1978).

Fish parasites can also be grouped according to life cycle. Those which have a direct life cycle do not require an intermediate host and can rapidly multiply and build up in high numbers. Other parasites have adapted to an indirect life cycle in which one

or more intermediate hosts are required in an obligate fashion for the parasite to survive. Infection then depends on the presence of the appropriate intermediate hosts. An understanding of the parasite's life cycle is essential in developing rational prevention and treatment strategies for the control of parasitic disease problems.

Ectoparasites

Protozoa Costia sp. is reported to infect many species of fish and can cause high mortality especially in younger age classes. This red-blood-cell-size protozoan flagellate attaches to the gills and external body surface of fish, causing irritation and host-cell death. Costia infections can occur at any time of the year, but they tend to be more prevalent in cooler weather in temperate regions. Costia sp. is cosmopolitan in distribution (Hoffman, 1971) and has a direct life cycle. Resistant cysts are not found. Costia is a horizontally transmitted water-borne parasite. The organism is thought to be an obligate parasite of cold-blooded species. Prevention can be achieved through elimination of carrier fish and provided parasite-free incoming water. Costia infections can be effectively treated in ponds with formalin 15-50 ppm, potassium permanganate 2-3 ppm, malachite green 0.1 ppm, or malachite green 0.1 ppm/formalin 15 ppm (Hoffman, 1979).

Ichthyophthirius multifilis (Ich) is reported to be the most detrimental parasite of pond-culture fresh- and brackish-water fish (Sairg, 1971; Rogers, 1978). Ichthyophthirius has been reported to destroy whole pond-fish populations (Bauer, 1961; Sairg, 1971; Rogers, 1979). All species of pond-cultured fish are thought to be susceptible. Ichthyophthirius multifilis is an obligate parasite of cold-blooded vertebrates. Ich is a large, ciliated protozoan with a prominent C-shaped nucleus. The adult parasite (trophozoite) burrows into the skin and gills of fish. Once mature, it drops off the fish, settles on the substrate, and undergoes multiple divisions, producing 1,000 or more infective tomites. The tomites or "swarmers" are most susceptible to available chemotherapeutics for Ich treatment. Ichthophthirius multifilis is cosmopolitan in distribution (Hoffman, 1971). Prevention is through elimination of exposure through destruction of carrier fish and through disinfection of potentially contaminated water or equipment. Protective immunity following initial exposure to Ich has been reported (Areerat, 1974); but vaccines for Ich are not presently available. In ponds, treatment with 0.1 ppm malachite green/15 ppm formalin for one to three treatments has been reported to be effective. Sairg (1971) reports that low oxygen (1-2 ppm) levels are inhibitory to I. multifilis.

Tricodina, Scyphidia, Glossatella, Epistylis, and Chilodonella These organisms are ciliated ectoparasitic protozoans that are frequently found to infect pond-cultured fish (Sairg, 1971; Rogers, 1979). More than one of these parasite species may be found to infect the same fish species. These parasites attack both the gills and the external body surface. Heavy infections are not uncommonly associated with poor environmental conditions. Of these ciliates, Chilodonella and Tricodina are reported to be the most damaging (Sairg, 1971). Heavy Chilodonella sp. infestation leads to high mortality in pond-cultured fish species in Israel (Sairg, 1971) and common carp cultured in Russia (Bauer, 1961). Epistylis sp. is thought in many cases to be a secondary invader growing in fungus-like colonies on damaged areas of the fishes' bodies. Tricodina, Scyphidia, Glossatella, Epistylis, and Chilodonella are cosmopolitan in distribution. These parasites have a direct life cycle; cyst stages are not formed. Prevention of disease caused by Chilodonella and Tricodina can be achieved through the elimination of carrier fish or water-borne contamination. Good husbandry practices and proper nutrition are very important in reducing the impact of these parasites on fish populations. Effective treatment for ponds include copper sulfate 0.25-0.5 ppm (do not use if the water hardness is less than 20 ppm), potassium permanganate 2-3 pm, formalin 15-25 ppm, or malachite green 0.1 ppm.

Platyhelminthes Monogenetic Trematodes Monogenetic trematodes are microscopic ectoparasitic flukes with a direct life cycle. Many generally are described as parasites of fish. Sairg (1971) states that monogenetic trematodes are the most numerous group of parasites found in Israel. Dactylogyrus vastator, D. anchoratus, and D. extensus are reported to be especially dangerous to susceptible fish species (Sairg, 1971). Monogenetic tremotodes are particularly pathogenic to fry and juvenile fish (Sairg, 1971; Hoffman, 1979), with mortalities reaching 80 to 100% in carp fry populations (Sairg, 1971). While species of monogenes are usually relatively host specific and may have a limited geographic distribution, as a group the monogenetic trematodes are cosmopolitan in distribution. Those monogenetic trematodes that infect fish are obligate parasites. Prevention is through elimination of carrier fish and use of parasite-free water. Treatments include the use of formalin 25-50 ppm (Hoffman, 1979); potassium permanganate 2-3 ppm (Hoffman, 1979); Masoten (Dipterex) (0, 0-dimethyl l-hydroxy 2-trichloromethyl phophate) 0.25 ppm (Sairg, 1971); D.D.V.P. (0, 0-dimethyl 0-2-2-dichlorovenyl phosphate) 0.25-0.40 ppm (Sairg, 1971); or Bromex (1, 2-dibromo-2, 2-dichloroethyl-dimethyl-phosphate) 0.15 ppm (Sairg, 1971).

Arthoropoda Crustacea Several parasitic Crustacea, including the branchiuran Argulus and the copepods Lernaea, Achtheres, and Ergasilus, are considered as extremely dangerous and reported to have caused great loss to fish culturists (Hoffman, 1970; Sairg, 1971; Rogers, 1979). The crustacean parasites are large ectoparasites visible to the naked eye. As a group they are obligate parasites, with a direct life cycle and are cosmopolitan in distribution. High mortality and growth reduction in pond fish species are attributed to parasitism by these organisms (Sairg, 1971). Transmission is horizontal. Argulus lays its eggs on substrata in the pond. The copepods carry eggs until they hatch. Prevention includes elimination of carrier fish and avoidance of contact with parasite-contaminated water.

Treatment methods include:

1. Chemotherapeutics
   Lindane (1, 2, 3, 4, 5, 6 -Hexachloro-cyclohexane 0.02 ppm) (Sairg, 1971)
   Malthion 0.25 ppm (Sairg, 1971)
   Dipterex 0.25 ppm (Sairg, 1971)
   D.D.V.P. 0.25 ppm (Sairg, 1971)
   Bromex 0.12 ppm (Sairg, 1971)

2. Mechanical - The placement, daily removal, and replacement of sticks in

the ponds; these serve as "egg traps" on which Argulus lay their eggs. Most Argulus eggs can be destroyed this way (Balarin and Hatton, 1979).

Annelidae Hirudinea (The Leeches) Leeches are reported to be a problem in cultured carp and channel catfish. Leeches are recognized as a problem in carp only in temperature regions. Pisciocola geometra (leech infecting common carp) is reported to have a wide distribution and is thought to serve as the vector for Trypanoplasma cyprini (hemoflagellate). T. cyprini infections are also restricted to cooler climates (Bauer, 1961).

Myxobdella lugubris affects catfish in the southeastern United States and may result in fish mortalities (Hoffman, 1979). Leeches have a direct life cycle with a cyst stage (cocoon) which is resistant to dessication (Bauer, 1961).

Bauer (1961) recommends the following bath treatments for Piscicola infections in carp.

2.5% NaCl for 1 hour
0.2% Lysol for 5-15 seconds
0.2% solution of unslaked lime for 2-5 seconds
0.005% solution of $CuCl_2$ for 15 minutes.

Masoten 0.50 ppm has also been suggested for pond treatment of leech infestation in catfish (Hoffman, 1979).

Endoparasites

Protozoa Myxosporidae Members of the subphylum Cnidospora, Class Myxosporidae, are parasitic to pond-cultured fish species. Sairg (1971) reports the occurrence of Myxobolus sp. infections in pond-cultured Mugil sp. in Israel. Myxobolus spp. and Henneguya spp. have been found to infect Cyprinidae, Cichlidae and Siluridae in Africa (Baker, 1960 cited in Sairg, 1971). Rogers, (1979) indicated that the interlamellar form of Henneguya sp. is thought to cause high mortality in catfish in the United States. Bauer (1961) reported the occurrence of pernicious anaemia and Hoferellasis in common carp in the Soviet Union as being caused by Myxobolus cyprini and Hoferellus cyprini respectively. Myxosporidian parasites can locate in many organ tissues but this varies from species to species. The mode of transmission is largely unknown. Prevention is through elimination of carrier fish and through pond disinfection (liming-calcium hydroxide 1,000 -2,500 lbs. per acre) (Wellborn, 1979). No effective chemical treatments have been reported.

Telosporea Coccidiosis is primarily an intestinal-tract disease reported to affect pond-cultured Cyprinids. Four species of the sporozoan parasite Coccidia infect the common carp in Europe (Bauer, 1961). Chinese carp are also reported to be susceptible to Coccidia infections (Bardach, Ryther et al., 1972). Coccidia produce two disease syndromes in cultured carp: coccidiosis and coccidal enteritis (each disease is caused by a different Eimera sp.). Coccidal enteritis is reported to cause serious losses in one-year-old common carp (Bauer, 1961). Coccidia are obligate intracellular parasites. The reported distribution of this disease is Europe and Asia. Preventative procedures include elimination of carrier fish, disinfection of ponds with lime, good husbandry practices, and proper nutrition. Specific chemotherapy for coccidiosis in fish is not reported.

Zoomastigophora The protozoan hemoflagellate Trypanoplasma cyprini is the cause of trypanoplasmosis in common carp in Europe (Bauer, 1961). The disease is not reported as a problem in pond-cultured Chinese or Indian carp species. In carp, T. Cyprini is believed to be transmitted by the leech Pisicola. Hemoflangellates (Trypanosoma and Trypanoplasma) are reported to affect channel catfish in the United States but are not a problem in pond culture settings (Rogers, 1979). Hemoflagellates are not reported to infect cultured tilapia, Mugil sp., Chanos chanos. Apparently, there is disagreement concerning the effect this parasite has on infected carp and on its significance is causing disease (discussed in Bauer, 1961). Control methods are not reported.

Platyhelminthes Digenetic Trematodes Digenetic trematodes are endoparasites that require one or more intermediate hosts for completion of the life cycle. In this regard fish may serve as intermediate or final hosts for these parasites. Many species of digenetic trematodes are reported to infect fish. Sairg (1971) reports digenetic trematodes to be of little consequence except as a public health problem such as Heterophyes heterophyes infections in Mugilidae. Hoffman (1979) suggests that channel catfish infected with the ovarian fluke Acetodextra ameimi may have reduced egg production. Bauer (1961) reports that the blood fluke Sanguinicola, which infects cultured common carp in the Soviet Union, causes mortality, particularly in young fish. Bauer (1961) also indicates that in the southern areas of the Soviet Union cultured carp may be 100% infected with "Black-spot disease" caused by encysted trematodes (metacercaria). Prevention and control procedures for digenetic trematodes include breaking a link in the life cycle. This may be achieved by reducing or eliminating snail intermediate hosts or final hosts like the heron from the pond habitat. Chemotherapy for fluke infectations in fish has not been developed.

Cestodes Cestodes (tapeworms) are reported to infect pond-cultured fish. Fish may serve as intermediate or final host for these parasites. Some tapeworms are rather benign, causing little damage to the host. Corallobothrium sp. infect catfish in the United States. This parasite is not reported to cause significant pathology or to be harmful to catfish (Hoffman, 1979). On the other hand, other species of tapeworms are considered dangerous to fish. Bauer (1969) maintained that Caryophylleaus fimbriceps infections resulted in mass mortalities in older common carp. The Asian tapeworm (Bothriocephalus acheilognathi) is considered an extremely dangerous parasite to cultured fish species (Hoffman, 1979). Preventative procedure for tapeworms include quarantine and restricted movement of infected stocks, and reduction or elimination of intermediate or definitive hosts. Control procedures include removal of infected fish from the pond followed by disinfection of the pond with calcium hydroxide 1,000 - 2,500 lbs. per acre (Wellborn, 1979). Chemotherapy is available for treatment of intestinal cestode infections. Di-n-butyl tin oxide and dibutyl tin dilurate 250 mg per kg of fish added to the feed or Yomesan (phenasal) at 0.5 percent of the weight of the feed for three days is reported as effective (Hoffman, 1979).

Aschelminthes Nematoda Many species of Nematoda have been reported to parasitize fish. Parasitic Nematoda life cycles are indirect, usually involving one or two intermediate hosts and a final host. Channel catfish cultured in the United States may harbor nematodes from four genera. Two of these, Spinitectus sp. and Contracaecum spiculigerum, are reported to be damaging to catfish (Hoffman, 1979). Hoffman (1970) lists Philometra carassii as dangerous to cultured species of fish, causing great losses. Balarin and Hatton (1979) point out that these parasites may become a problem in situations where predatory birds, that may serve as final hosts for nematodes, are abundant. Prevention and treatment methods include breaking the life cycle (controlling intermediate or final hosts) (Balarin and Hatton, 1979). Masoten has been reported as effective in controlling Camallanus spp. in aquarium fish (Hoffman, 1979).

Acanthocephla There are at least five genera of Acanthocephla that are known to infect fish. Fryer and Iles (1972 cited in Balarin and Hatton, 1979) reported Acanthocephla as common in African cichlids. Acanthocephla are reported to parasitize all species of pond-cultured fish in this discussion except Chanos chanos. Nevertheless, members of this phyla have not been reported as the cause of disease or problems under pond-cultured conditions. The Acanthocephla that infect fish have indirect life cycles with fish serving as intermediate or final hosts. Control methods have not been implemented for Acanthocephla in pond-cultured fish.

NON-INFECTIOUS DISEASES

Diseases of Nutritional Etiology

In general, nutritional diseases are not recognized as a problem in warmwater pond-fish culture unless stocking rates approach or exceed 4,000 kg/ha. This is believed to be due to the availability of natural foods in the pond environment. Launer, Tiemeier, and Deyoe (1978) reported no significant difference in weight gain, feed conversion, or survival in channel catfish in ponds fed diets deficient in vitamins C and D_3 (cholecalciferol) for five months compared to controls fed diets with these vitamins. Lovell and Lim (1978) reported that when channel catfish are stocked at densities of less than 4,000 kg/ha there is sufficient vitamin C in ponds to prevent "broken back syndrome" in fish fed diets without vitamin C.

Nutritional problems in fish populations may appear in the form of reduced fecundity, slowed growth, decreased appetite, increased susceptibility to infectious disease, frank morbidity with clinical signs and pathological lesions, mortality, or some combination of the above. It is well known that prolonged storage of feed may result in reduction of feed quality, particularly for vitamin C and the essential fatty acids (Lovell, 1976; National Academy of Sciences, 1977).

The National Academy of Sciences (1977) reported that a great deal of nutritional research data exists for channel catfish and the common carp, but that there is limited information for tilapias, milkfish, Chinese carps, and most other warmwater pond-cultured species. The following discussion on reported nutritional deficiency problems is necessarily centered on channel catfish and common carp.

Deficiency Diseases

Starvation Starvation refers to absolute nutrient deprivation resulting from inadequate intake or assimilation of feed. The energy needs of the organism are below maintenance levels. Typically, starved fish will have a large head and slender body and will be dark in coloration.

Protein and Amino Acids In warmwater fish species, specific protein and amino-acid deficiency diseases are generally not recognized as a problem in pond-culture settings. Dietary protein in these fishes supplies both essential amino acids and energy. Feeding experimental diets deficient in selected amino acids causes appetite depression and poor growth regardless of the type of amino acids omitted (Lovell, 1976; National Academy of Sciences, 1977; Cowey and Roberts, 1978). Cridland (1960, cited in Balarin and Hatton, 1979) reported growth suppression, skeletal deformities, and exophthalmia in S. esculentus fed maize meal, deficient in tryptophan (Gohl, 1975, cited in Balarin and Hatton, 1979). A tryptophan-deficiency-related scoliosis has been reported for salmonids (Ashley, 1972). Lovell (1976) suggested the occurrence of tryptophan-deficiency-induced scoliosis was unlikely in warmwater fish fed practical diets. Lovell (1976) found growth suppression in pond-reared channel catfish resulting from feeding diets with high protein levels (42%) in the presence of low amounts of non-protein energy.

Lipids Specific fatty-acid requirements have not been established for channel catfish (Lovell, 1976) or for other warmwater species. Yet an essential fatty-acid-deficiency syndrome, which results in growth reductions and tissue build-up of 5, 8, 11-eicosatrienoic acid, has been reported in catfish, carp, and eel (National Academy of Sciences, 1977). Lipoid liver degeneration, an essential-fatty-acid deficiency disease reported in salmonids (Cowey and Roberts, 1979), is not known to occur in pond-cultured warmwater species. Tilapia and carp apparently can tolerate dietary lipid content above 25% (Lagler et al., 1962, cited in Balarin and Hatton, 1979).

Carbohydrates The utilization of carbohydrate as an energy source by warmwater fish is unclear (National Academy of Sciences, 1977). Research data suggest that dietary lipids and proteins are utilized preferentially to carbohydrates as energy sources in warmwater fish species (National Academy of Sciences, 1977). Sekoke disease, described as a spontaneous diabetes in carp fed extremely high-starch diets, has been reported in Japan (Yokote, 1970, cited in Lovell, 1976). The disease can be prevented by eliminating the excess starch from the diet.

Vitamins Vitamins are essential in warmwater fish diets. If intake levels are inadequate, specific deficiency signs may become apparent (Table 1). Vitamin-deficiency disease is unlikely to occur in pond-culture settings unless stocking densities are considerable. "Broken back syndrome" is well-known disease of channel catfish cultured under hyperintensive conditions. This disease has been reported in heavily stocked catfish ponds (6270 kg/ha) or in catfish ponds stocked with large numbers of tilapia (Lovell, 1976). As previously mentioned in the

Table 1

THE ESSENTIAL VITAMINS AND DEFICIENCY SIGNS IN WARMWATER FISHES[a]

Vitamin	Deficiency signs
Thiamine	Poor appetite, muscle atrophy, convulsions, instability and loss of equilibrium, edema, poor growth, congestion of fins and skin, fading of body color, lethargy.
Riboflavin	Corneal vascularization, cloudy lens, hemorrhagic eyes, photophobia, incoordination, abnormal pigmentation of iris, striated constrictions of abdominal wall, dark coloration, poor appetite, anemia, poor growth, hemorrhage in skin and fins.
Pyridoxine	Nervous disorders, epileptiform fits, hyperirritability, ataxia, anemia, loss of appetite, edema of peritoneal cavity, colorless serous fluid, rapid onset of rigor mortis, rapid breathing, flexing of opercles, irridescent blue coloration, exophthalmos.
Pantothenic acid	Clubbed gills, necrosis, scarring and cellular atrophy of gills, gill exudate, prostration, loss of appetite, lethargy, poor growth, hemorrhage in skin, skin lesions and dermatitis.
Inositol	Distended stomach, increased gastric emptying time, skin lesions, poor growth.
Biotin	Loss of appetite, lesions in colon, altered coloration, muscle atrophy, spastic convulsions, fragmentation of erythrocytes skin lesions, poor growth.
Folic acid	Lethargy, fragility of caudal fin, dark coloration, macrocytic anemia, poor growth.
Choline	Poor food conversion, hemorrhagic kidney and intestine, poor growth, accumulation of neutral fat in hepato-pancreas, enlarged liver.
Nicotinic acid	Loss of appetite, lesions in colon, jerky or difficult motion, weakness, edema of stomach and colon, muscle spasms while resting, sensitivity to sunlight, poor growth, hemorrhage in skin, tetany, lethargy, anemia.
Vitamin B_{12}	Poor appetite, low hemoglobin, fragmentation of erythrocytes, macrocytic anemia, reduced growth.
Ascorbic acid	Scoliosis, lordosis, impaired formation of collagen, abnormal cartilage, eye lesions, hemorrhagic skin, liver, kidney, intestine, and muscle, reduce growth.
Vitamin A	Ascites, edema, exophthalmos, hemorrhagic kidneys, poor growth.
Vitamin E (α-tocopherol)	Ascites, ceroid in liver, spleen, and kidney, epicarditis, exophthalmia, microcytic anemia, pericardian edema, fragility of red blood cells, poor growth.
Vitamin K	Anemia, prolonged coagulation time.

[a] From National Academy of Sciences, 1977.

deformed spinal column, opercula and gill filaments, caudal fin erosion, anemia, reduced growth rate, increased susceptibility to bacterial pathogens, and reduced tissue levels of vitamin C (Lovell, 1976). Broken back syndrome arises if channel catfish are fed diets deficient in vitamin C for periods longer than eight weeks. The minimum dietary requirement for vitamin C in channel catfish is 30 mg/kg of diet (Lovell, 1976).

Sato, Yoshinaka, et al. (1978) found that the absence of vitamin C in the diet of carp cultivated under normal conditions for 84 weeks did not slow growth, increase mortality, or reduce liver concentrations of ascorbic acid. On the other hand,

Mahajan and Agrawal (1979) reported poor growth, high mortality (42%), severe hemorrhages, fin necrosis, increased pigmentation, and spinal flexures in Indian carp (Cirrhina mrigala) feed diets lacking in vitamin C. These experiments were conducted in 12-liter plastic troughs and plastic pools that are cleaned each day to remove algae growth and detritus.

Minerals Fish absorb minerals from both feeds and the water (Lovell, 1976; National Academy of Sciences, 1977). Calcium and phosphorus are the minerals known to be required in the largest quantities by fish (Lovell, 1976). Fish can obtain adequate levels of calcium from the water unless the water is very soft. Phosphorus is not absorbed as well from the water, and dietary intake of phosphate is required by warmwater fish (National Science Foundation, 1977). Lovell (1976) found that experimental phosphorus deficiency in channel catfish caused decreased growth rate and increased mortality. In carp, inadequate phosphate intake results in slowed growth, scoliosis, lordiosis, and skull and opercular deformities (National Academy of Sciences, 1977). Scott (1977, cited in Balarin and Hatton, 1979) described deformities, in tilapia farmed in Kenya caused by calcium and phosphorus dietary imbalances. The minimum requirements of available phosphorus for carp are 0.8% and for channel catfish 0.45% of the diet (National Science Foundation, 1977).

The dietary requirements of other minerals have not been established for warmwater fishes. Experimentally, high levels of potassium, iron, zinc, copper, iodine, and molybdenum have caused growth depression in fish. Diets low in iron and copper have been reported to cause anemia in fish (National Academy of Sciences, 1977; Sakamoto, 1978). Mineral deficiencies are not known to cause problems in pond-culture settings. Ishac and Dollar (1968) reported that tilapia kept in manganese-free water and fed manganese-deficient diets were sluggish, developed equilibrium problems, had poor appetites, lost weight, and began to die after three weeks. These authors calculated a minimum daily requirement of 1.7 mg manganese per kilogram of fish for normal growth.

Diseases with a Toxic Etioilogy

In tropical pond-aquaculture systems, toxicological problems are those resulting from exposure to inorganic, synthetic organic, or natural organic toxicants. Inorganic toxicants of significance to pond-aquaculture systems include ammonia, nitrite, and hydrogen sulfide. Synthetic organic toxicants are the pesticides and herbicides. Natural organic substances are the biotoxins. In this category only the phytotoxins have been recognized as toxicants in tropical aquaculture systems.

Low dissolved oxygen, the most significant cause of fish mortality in warmwater pond aquaculture, is discussed in the section on water quality.

Exposure of animals to sufficient concentrations of toxicants may result in death, illness, or physiopathologic alternation. In aquaculture systems these effects can cause decreased survival, reduced growth, increased susceptibility to disease, or impaired fecundity, resulting in suboptimal yields and loss of profits. At toxicant exposure levels that result in acute mortality the effect is readily apparent and corrective procedures may be implemented. Sublethal effects of toxicants may be difficult to detect until some time after exposure when pond yields reflect poor performance of the stock.

Inorganic Toxicants

Ammonia Ammonia is present in most natural waters and results from biological degradation of nitrogeous organic matter (Environmental Protection Agency, 1976). When ammonia dissolves in water a chemical equilibrium is established which contains un-ionized ammonia (NH_3), ionized ammonia (NH_4^+), and hydroxide ions (OH^-). The equilibrium shifts in favor of increased NH_3 with increasing pH (Environmental Protection Agency, 1976). The un-ionized form of ammonia (NH_3) is toxic to fish. Toxicity varies with fish age and species.

Ammonia toxicity has been suggested as a limiting factor in channel catfish culture (ponds) in the United States (Avault, 1978). Problems arise in catfish ponds at high stocking densities (5,000 catfish per acre). Recommended control methods include management practices, proper feeding and stocking levels, and rearing in ponds not deeper than 1.5 meter (Avault, 1978).

The un-ionized ammonia 96 hr. LC50 values for channel catfish fry at 22°C, 26°C, and 30°C are 2.4 mg/L, 2.9 mg/L, and 3.8 mg/L (Colt and Tchobanoglous, 1976). Growth suppression in channel catfish resulting from exposure to sublethal levels of NH_3 has been reported (Robinette 1973; Colt and Tchobanoglous, 1978). The safe level of un-ionized ammonia for freshwater aquatic life is 0.02 mg/L at temperature $> 5^{\circ}C$ and pH < 8.5 (Environmental Protection Agency, 1976).

Common carp are considered to be relatively resistant to acute ammonia toxicity (Environmental Protection Agency, 1976). On the other hand differences in sensitivity among fish species to chronic exposure is considered small (European Inland Fisheries Advisory Commission, 1970 cited in Environmental Protection Agency, 1976).

Acute ammonia toxicosis causes metabolic acidosis and hyperkalemia resulting in heart block (Buck, 1973). In chronic sublethal exposure, ammonia acts as a tissue irritant, causing gill epithelial hyplerplasia and focal necrosis in the liver (Smith and Piper, 1975). Burrows (1964, cited in Smith and Piper, 1975) suggests that chronic sublethal exposure to un-ionized ammonia may predispose fish to infectious disease. Flis (1968, cited in EPA, 1976) reported that exposure of common carp to sublethal ammonia levels resulted in cellular necrosis in several organ systems.

Nitrite - Nitrate Nitrite toxicity (brown-blood disease) has been reported as a cause of significant losses in channel-catfish pond culture in intensively fed ponds at the time of sharp decline in temperature in late fall or early winter (Lovell, 1979). Nitrite is an intermediate compound in the biological oxidation of ammonia. Nitrate is relatively non-toxic but may be reduced to nitrite. Nitrite absorbed into the fish oxidizes hemoglobin to methemoglobin. Methemoglobin in the oxidized state is not available for oxygen transport, resulting in decreased oxygen-carrying capacity of the blood and death through tissue anoxia (Buck, 1973).

Both acute and chronic toxic effects of nitrite/nitrate are reported for domestic animals (Buck, 1973). Only the acute toxic effects have been reported for fish (Lovell, 1979). The nitrite 96 hr. LC 50 level for channel catfish at 22 and 30°C are 42 and 43 ppm respectively (Colt and Tchobanoglous, 1976). Nitrite nitrogen levels below 5 ppm (McCoy, 1972 cited in Environmental Protection Agency, 1976) and nitrate nitrogen levels below 90 ppm (Knepp and Arbin, 1973 cited in Environmental Protection Agency, 1976) should be safe for most warmwater fish species.

Reduction of feeding rate is suggested by Lovell (1979) as a means to control nitrite levels in pond water. Increased water flow into the pond may also be effective in reducing nitrite levels in ponds.

Hydrogen Sulfide Hydrogen sulfide toxicity is considered to be a problem in intensive fish pond culture systems in the southern United States (Johnston, 1975). The anaerobic decomposition of algae and uneaten feed is the major source of hydrogen sulfide in pond systems. In well-oxygenated water the effect of sulfide on fish is minimal because it is oxidized to non-toxic sulfate or sulfur. The degree of hazard to aquatic animals from sulfide depends on temperature, pH, and dissolved oxygen (Environmental Protection Agency, 1976). At neutral or lower pH and low dissolved oxygen levels the hazard from sulfides is exacerbated. Sulfide levels that exceed 2.0 mg/L may constitute a long-term health hazard to pond-cultured fish (Environmental Protection Agency, 1976).

Synthetic Organic Toxicants (Pesticides and Herbicides) Synthetic organic toxicants (pesticides and herbicides) may enter pond aquaculture systems through the purposeful or inadvertent activities of man. It is well documented that contamination with these substances may be highly detrimental to fish and members of the pond ecosystem. This is a recognized problem on a worldwide scale (FAO, 1964). Koesoemadinata (1980) states that pesticides can be a major constraint in integrated farming by reducing productivity of fish or other aquatic animal crops reared simultaneously or as alternative crops.

The nature of some of these compounds, especially the chlorinated hydrocarbons, is such that they persist and are concentrated in the food we eat. Koesoemadinata (1980) points out that synthetic organic toxicants can affect fish production, the consumers of fish, and fisheries resources. The effect on fish may be direct or indirect through reduction of food organisms in the food web. The FAO has developed a policy statement regarding the use of pesticides as it relates to fish culture and fisheries resources (FAO, 1964). Extreme caution is advised in the use of pesticides and herbicides where there is any likelihood of contamination of fish culture or fisheries resources areas.

Biotoxins (Phytotoxins)

Chrysomonadinae Prymnesium parvum is a phytoflagellate inhabiting brackish water and produces powerful exotoxins capable of causing high mortality in pond-reared fish. Sairg (1971) reports the economic loss to fish farmers in Israel to have exceeded $100,000 in some years. Fish mortalities resulting from Prymnesium parvum have been reported in Israel, England, Europe, the United States, Bulgaria, and Japan (Sairg, 1971). P. parvum does not grow at salinities below 10% (Shilo and Shilo, 1962, cited in Sairg, 1971).

The toxins produced by P. parvum affect many invertebrates and all cultured teleosts (Sairg, 1971). Mortality in pond cultured fish may reach 100%. The toxicity of P. parvum toxin to fish is highly dependent on complexing with a cation at pH 7 to 9. The icthythotoxin affects the gills by destroying the selective permeability of the epithelial cells. Death ensues due to osmotic shock and intravascular hemolysis.

Ulitzur and Shilo (1964 cited in Sairg, 1971) developed a sensitive bioassay to detect the presence of levels of P. parvum toxin in pond water. This procedure which utilizes Gambusia sp. as a test fish, allows for the early detection and treatment of dangerous levels of toxins in the ponds. The application of this procedure has led to the prevention of fish mortality in 95% of infested ponds and has significantly reduced economic losses.

Sairg (1971) lists aqua-ammonia, ammonium sulfate, and copper sulfate as effective treatments of ponds to control P. parvum.

Cyanophycophyta (Blue-Green Algae)

Of the more than 50 genera of blue-green algae known, only 10 or so have been reported to cause toxicosis in fish, birds, or mammals (Collins, 1978). Blue-green algae like Microcystis aeruginosa produce endotoxins that are released upon cell lysis. Others, like Anabaena flos-aquae, excrete a water-soluable exotoxin. Blue-green algae are reported to cause fish mortalities due to excretion of toxic substances and through oxygen depletion following mass algae die-offs (Sairg, 1971). Not all isolates of a blue-green species will produce toxins, and toxin production can be activated or inhibited by a variety of environmental conditions (Collins, 1978). Sairg (1971) reported that carp injected with Microcystis aeruginosa endotoxin developed central nervous system signs (loss of equilibrium and spiraling).

Sairg (1971) reports that a "muddy" flavor in fish flesh, which resulted in considerable economic loss due to lack of acceptability of product by consumers, was caused by the fish feeding on Oscillatoria limosa and Anabaena spiroides.

Sairg (1971) recommends the control of blue-green algae blooms with copper sulfate, but cautions that copper sulfate is not at all selective for blue-greens. In addition, application of copper sulfate may lead to acute algae die-offs, causing fish mortalities through oxygen depletion. Dissolving copper sulfate in warmwater at a 3% concentration and selectively spraying the corners and shores where floating blue-green algae accumulate is suggested. Total copper applied should not exceed 1.5 ppm (Sairg, 1971).

COMPETITORS, PESTS AND PREDATORS

In pond aquaculture systems, competitors, pests, and predators are deleterious fauna that cause production or financial losses. The impact of these organisms is particularly evident in extensive pond culture settings. Losses occur through reduced yields of

Table 2

SUGGESTED SAFE LEVELS FOR SOME PESTICIDES FOR AQUATIC LIFE[a]

Chemical	Safe level[b]	Bioaccumulation index	Persistence index
Aldrin/Dieldrin	0.003 mg/L	High	High
Chlordane	0.01 mg/L (F) 0.004 mg/L (m)	High	High
DDT	0.001 mg/L	High	High
Demeton	0.01 mg/L	?	?
Endosulfan	0.003 mg/L (F) 0.001 mg/L (M)	?	Low
Endrin	0.004 mg/L	Low	Low
Guthion	0.01 mg/L	Low	Low
Heptachlor	0.001 mg/L	High	High
Lindane	0.01 mg/L (F) 0.004 mg/L (M)	Moderate	?
Malathion	0.1 mg/L	Low	Low
Methoxychlor	0.03 mg/L	Low	Low
Mirex	0.001 mg/L	High	High
Parathion	0.04 mg/L	Low	Low
Toxaphene	0.005 mg/L	High	High
Polychlorinated Biphenyls	0.001 mg/L	High	High

[a] Adapted from Environmental Protection Agency, 1976

[b] (F) = freshwater, (M) = marine

desirable species or result from damage to pond surfaces or structures (Pillai, 1970). Competitors reduce fish production through competition with cultured species for food and habitat, resulting in depressed growth and survival of the latter. Pests damage pond surfaces or structures in ponds. Predators decrease numbers of cultivated fishes, resulting in production losses. In certain circumstances predator biomass control can result in production increases (discussed in the section on stocking procedures).

Competitors

Snails are some of the most common competitors in fresh-and brackish-water ponds. Snails in the family Cerithidae are reported to be particularly troublesome in the Indo-Pacific region (Pillai, 1970). Snails compete with herbivorous fish for available algae feeds, slow the growth of desirable algae species, and in some instances destroy habitat (Pillai, 1970). Ling (1960, cited in Pillai, 1970) states that snails compete for algae with milkfish in brackish-water fish ponds. Snails may also serve as intermediate hosts for several fish, bird, and mammal parasites.

If they are not abundant, snails may be beneficial as scavengers, but if they are allowed to multiply unchecked they may accumulate in large numbers. As much as 34 tons of snails have been recovered from fish ponds in East Java (Ling 1960, cited in Pillai, 1970). Djajadiredja (1957, cited in Pillai, 1970) found as many as 6,940 snails/m^2 in ponds in Djakarta.

The Polychaete worm Dendronereis pinnaticirris is reported to infest brackish-water ponds in the Philippines and seriously deplete algae biomass, thus reducing available algae for milkfish (Pillai, 1970).

Another competitor is the larval Chironomid midge (Tendipes, longilobus). These organisms are reported to occur in high numbers in brackish-water ponds in the Philippines and compete with milkfish fry and juveniles for blue-green algae (lab-lab) in the ponds (Ling, 1977). Chronomid larvae are reported to consume 60-90 kg/algae/day (Bardach, Ryther, et al., 1972).

Bardach, Ryther, et al. (1972) mention that tadpoles and fairy shrimps (Streptocephalus texanus) are competitors with catfish fry for available feed in catfish ponds in the United States.

Undesirable species of fish in fresh and brackish water ponds are the most serious competitors to desirable species. Sarotherodon mossambica, Gambusia affinis, Mugil sp., Scatophagus sp. and Mollienesia latipinna are reported as competitors in milkfish ponds in the Philippines and Taiwan (Pillai, 1970; Bardach et al., 1972).

Pests

In the context used here, pests are those co-inhabitants of fish ponds that mechanically damage fish pond surfaces or structures within ponds. Pillai (1970) mentions that oysters and barnacles occasionally pose a problem by fouling screens and sluices, thereby hindering free exchange of water in brackish water ponds in the Indo-Pacific region.

Wood-boring organisms are reported to cause considerable damage to wooden structures in ponds (Pillai, 1970). Molluscs in the family Teredinidae (genus Teredo - 11 species, genus Bankia - six species, and genus Nausitora - one species) and the family Pholadidae (genus Martesia) attack and eventually destroy wooden objects in ponds (Pillai, 1970). Wood-boring amphipods and isopods are also known to destroy wooden structures in ponds (Pillai, 1970). In India the most important genera are Sphaeroma and Limnoria (FAO/UN, 1958, cited in Pillai, 1970).

Through burrowing activities in the pond bottom, Bristleworm (Polychaetes) cause damage that results in water losses (Pillai, 1970). Several species of burrowing crabs (Scylla serrata, Sesarma taeniolata, Uca sp. and the large crustacean Thalassina scorpinnoides) are reported by Pillai (1970) to burrow into pond bottoms and dykes, causing leaks.

In the Philippines, the mucilaginous egg masses of the Polychaete worm Marphysa gravelyi are reported to cause appreciable losses to milkfish fry and fingerlings that accidently swim into and become stuck to these egg masses (Pillai, 1970).

Predators

Piscivorous fish, amphibians, reptiles, birds, and mammals are reported to cause considerable losses of fish stocks in fresh and brackish water pond culture systems (Bardach, Ryther, et al., 1972; Balarin and Hatton, 1979; Pillai, 1970).

Fishes

Pillai (1970) lists numerous species of predatory fish that are a problem in brackish-water pond culture in the Indo-Pacific Region. Some of the major predatory species in this region include Elops hawaiiensis, Megalops cyprinoides, Epinephelus spp., and Sphyraena spp. Balarin and Hatton (1979) mention that predatory fishes cause losses to cultured tilapia in Africa.

Reptiles and Amphibians

Piscivorous aquatic snakes cause substantial losses to juvenile fish in ponds. Sairg (1971, cited in Balarin and Hatton, 1979) reported up to 300 snakes (Natrix natrix) caught in ten traps in two weeks in a 0.2 ha pond. The snake Cerberus rhynchops has been reported by Djajadiredja (1957, cited in Pillai, 1970) to be a pond predator in Java. Balarin and Hatton (1979) reported that African toads of the genus Xenopus cause losses in tilapia nursery ponds.

Avian Predators

Birds are reported to be some of the most destructive predators of pond-cultured fish (Balarin and Hatton, 1979; and Pillai, 1970). Chimits (1957, cited in Balarin and Hatton, 1979) reported that a pelican can consume between 1-3 tons of fish in a year. Schaeperclaus (1933, cited in Pillai, 1970) stated that herons may cause losses of up to 30-40% of fry and juvenile fishes cultured in ponds. Fryer and Iles (1972, cited in Balarin and Hatton, 1979) report that a heron consumes as much as 100 kg of fish per year.

Mammalian Predators

Otters (Lutra maculicollis and Aeonyx capensis) are considered extremely destructive and have been reported to reduce fish stocks as much as 80% (Marr, Mortimer, and van der Lingen, 1966, cited in Balarin and Hatton, 1979).

PREVENTION AND CONTROL PROCEDURES FOR COMPETITORS, PESTS AND PREDATORS IN POND AQUACULTURE SYSTEMS

In pond aquaculture systems prevention and control procedures for competitors, pests, and predators can be classified as physical, chemical, or biological. The choice of a prevention and control procedure is frequently determined by the past experience of the pond manager. Once an effective method is known, efforts to find more efficacious procedures are often not attempted. Physical and chemical procedures are frequently used in combination.

Preventative Procedures

Physical and chemical methods are employed as preventative procedures in pond aquaculture systems. Physical methods to prevent the introduction of unwanted predatory or competitive species of fish in ponds include draining and drying of ponds prior to stocking and screening the inflow water.

Chemical methods are used to prevent the attack of wood-boring mollusces (Polychaetes) or crustaceans on wood structures in ponds. Pillai (1970) reports the treatment of wood with antiborer formulations such as creosote, other oil preservatives, copper compounds, and thick coating of tar in the Indo-Pacific Region. As pointed out by Pillai (1970) these treatments are not indefinitely effective in preventing attack by the wood-boring pests.

Some species of predatory birds can be discouraged from entering ponds by extending fencing into the shallows of the pond (Marr et al., 1966, cited in Balarin and Hatton, 1979) or by stringing wire strands along the edges of or across ponds (Balarin and Hatton, 1979). Scare devices such as scarecrows, bamboo rattles, empty-can rattles, bells, flashguns, sirens, klaxon horns, and gongs are reported by Pillai (1970) to be effective deterrents to avian predators. Marr et al. (1966, cited in Balarin and Hatton, 1979) reported that fencing was effective in preventing entry of otters into fish ponds.

Physical Methods

Physical, chemical, and biological methods are employed to control competitors, pests, and predators in pond aquaculture systems. Ling (1960, cited in Pillai, 1970) reported that the collection and removal of unwanted snails was effective in controlling these competitors in milkfish ponds in the Philippines. Pond drying in conjunction with the use of chemicals is mentione by Pillai (1970) as beneficial in controlling snails.

Oysters, barnacles, and Polychaete worms that foul screens and sluices in ponds can be effectively controlled by periodic drying and physical removal by hand (Pillai, 1970). Problems caused by wood-boring molluscs and crustaceans can be partially controlled by periodic removal and drying of wooden structures in ponds (Pillai, 1970). Traps and other methods of physical removal are reported by Pillai (1970) to be effective in controlling burrowing crabs and other crustacean pests found in brackish-water ponds in the Indo-Pacific Region. Huet (1972, cited in Balarin and Hatton, 1979) report that toads (genus Xenopus) in African ponds can be trapped or captured for removal. Sairg (1971) reports that predatory snakes can be controlled by trapping or can be killed by workers. Pillai (1970) stated that predatory birds and otters may be controlled by trapping or shooting.

Chemical Methods

A number of chemicals are used to control competitors, pests, and predators in fresh- and brackish-water ponds. Both natural substances and synthetic compounds are used. Ling (1960, cited in Pillai, 1970) reported that heavy application of green manure in ponds will result in destruction of snail competitors. Pillai (1970) reported that application of molasses into the pond has some beneficial effect in controlling snails. The mechanism of action of these substances on snails was not given.

Tea seed (Camellia drupisera) has wide use as a biocide in ponds in the Indo-Pacific Region. The active principle is saponin. Pillai (1970) recommends it be used following pond drainage to control snails and unwanted fish. Reported application rates are 15-18 kg/ha (Tang, 1967, cited in Pillai, 1970); 180 kg/ha (Djajadiredja, 1957, cited in Pillai, 1970) and 200 kg/ha (Bardach, Ryther, et al., 1972). Saponin applied at 0.5 ppm has been recommended to control competitive and predatory species of fish in Philippines milkfish ponds prior to stocking (Bardach, Ryther, et al., 1972).

Tobacco wastes (tobacco dusts) are also widely advocated as a biocide to control snails, polychaete worms, and competitor and predator fish in Indo-Pacific ponds (Bardach, Ryther, et al., 1972; Pillai, 1970). The active principle in tobacco byproducts in nicotine. In milkfish ponds in the Philippines tobacco dust is applied at 12-15 kg/ha (Tang, 1957, cited in Pillai, 1970). Pillai (1970) reports that polychaete worms are also controlled by 2 ppm nicotine in the water.

Rotenone, derived from the derris plant, is widely used as a natural piscicide. Reported application rates vary; 0.5 ppm (Hall, 1949, cited in Pillai, 1970), 4 gm/m^3 (Djajadiredja, 1957, cited in Pillai, 1970) and 20 ppm (Alikunki, 1957 cited in Pillai, 1970).

Quicklime applied to the pond bottom after draining and drying is recommended as an effective biocide to control snails, unwanted fish, and disease organisms. Application rates of 1000 kg/ha are reported as effective (Bardach, Ryther, et al., 1972; Tang, 1967, cited in Pillai, 1970).

Synthetic organic and inorganic toxicants are used to control unwanted competitors, pests, and predators in dirt ponds. Pillai (1970) recommend that use of Bayluscide at 3 ppm in partially drained pond water to control unwanted snails and polychaete worms.

Phenol is added to pond water after most of the water is drained to control polychaete worms, even those which are deeply burrowed into the mud (Pillai, 1970). Chemical techniques used to control crab pests in the Philipines include spraying a 10% solution of technical BHC (containing 6.5% gamma isomer) or applying a few cc of kerosene into each crab burrow.

Endrin applied at 0.1 ppm (Hickling, 1962, cited in Pillai, 1970) or 340 gms in 45 liters of water in drained ponds (Pillai, 1962, cited in Pillai, 1970); D.D.T. applied at 0.03 gm/liter (Rabanal and Hosillos, 1957), cited in Pillai, 1970); and 2,4-D applied at 0.13 gm/liter (Rabanal and Hosillos, 1957, cited in Pillai, 1970) have been advocated to control unwanted fish in ponds.

Tadtox is mentioned by Bardach, Ryther, et al. (1972) as being used to control unwanted tadpoles in ponds in the United States.

Pillai (1970) mentions the use of poisoned baits to control reptilian and avian predators, but the types of poisons were not given.

PUBLIC HEALTH CONSIDERATIONS IN WARMWATER POND AQUACULTURE

Public health diseases in pond aquaculture are zoonoses (diseases of animals which are transmitted to man) or diseases of man whose prevalence is increased through aquaculture activities. These diseases can be classified as (1) those that affect the consumer and (2) those that affect pond workers or people living in close proximity to ponds.

Consumer Related Diseases

There are five bacterial diseases of man (Salmonellosis, Shigellosis, Vibrio gastroenterities, Botulism, and Clostridium perfringens enterotoxemia) that have been associated with the consumption of contaminated fish products (WHO/FAO, 1968; FAO/WHO, 1973/Hobbs, 1979; Bryan, Fanelli, and Riemann, 1979; and Sakazaki, 1979). Specific cases of human bacterial disease that resulted from consumption of pond-raised tilapia, catfish, carps, mullet, or milkfish are apparently not present in the literature. This is surprising in view of the common practice in many areas of the world of fertilizing with human and animal wastes. Apparently this practice has not resulted in significant outbreaks of human bacterial infection or intoxications, or at least reports regarding such outbreaks are lacking in the published literature.

A survey of fresh and frozen commerically caught and pond-reared channel catfish in the southern United States indicated that 93-94.5 percent of the fresh and frozen catfish met the proposed quality standards of less than or equal to 10 organisms per gram (FDA, 1977). The report further stated that catfish have never been definitely incriminated in human outbreaks of food-borne illness caused by Salmonella (FDA, 1977). For additional information regarding human bacterial infections or intoxications the reader is referred to WHO/FAO, 1968; FAO/WHO, 1973; Bryan et al., 1979; Hobbs, 1979; and Sakazaki 1979.

Fish, particularly freshwater fish, can be intermediate hosts for a number of metazoan parsites that can infect man. The more important parasites transmissible to man through the consumption of raw or improperly processed fish flesh include:

1. The broadfish tapeworm (Diphyllobothrium latum), which is spottily distributed in parts of Europe, Asia, Australia, and North and South America (Healy, 1979).
2. The flukes Clonorchis sinensis, Opisthorchis spp., members of Heterophyidae, and Metagonimus Yokagawai. These fluke parasites are common in Asian countries and are non-specific in fish species they infect (Healy, 1979; Bauer, 1961).

Fish are the second intermediate hosts for each of these parasites. These parasites encyst in muscle or other organ tissues of the fish. Human infection results from ingestion of improperly cooked or processed contaminated fish tissues. Prevention and control of human disease from these parasites include proper sewage disposal, snail control, adequate cooking, and adequate freezing of fish products (FAO/WHO, 1973).

The use of raw human excrement as a pond fertilizer is thought to result in a high prevalence of intestinal parasitism among Chinese people who eat pond fish (Hickling, 1962). Wykoff and Winn (1965, cited in Healy, 1979) estimate that over 3.5 million people are infected with Opisthorchis viverrini in Thailand, China, Laos, and Vietnam. These infections resulted from the consumption of improperly cooked or processed fish flesh. Whether these fish were pond cultured or captured from streams was not mentioned.

Detailed information regarding these parasitic diseases of man can be found in Bauer (1961) and Healy (1979).

Fish are not known to transmit virus or fungal organisms pathogenic to man (Janssen, 1970).

A potential problem is human toxicosis resulting from the consumption of fish flesh contaminated with drugs and drug metabolities, toxic elements, or contaminants of natural or industrial origin (FDA, 1977). Specific cases of human toxicosis following consumption of aquacultured channel catfish, Chinese catfish, milkfish, mullet, tilapia, and carps were not found by this author. Nevertheless, caution is advised regarding the addition of any element or compound which could be selectively absorbed and concentrated in fish flesh and which may constitute a public health hazard to the consumer.

Nonconsumer Related Diseases

Leptospirosis

Leptospirosis, a sometimes fatal, systemic bacterial disease of mammals, is known to be transmitted through contact with urine or water contaminated with viable Leptospira (Kenzy and Ringen, 1971). This zoonotic disease has a worldwide distribution. Leptospirosis is considered an occupational hazard of agricultural workers, abattoir and fish handlers, sewer workers, veterinarians, and other groups that are in frequent contact with wild or domestic mammals.

While pathogenic Leptospira are known to survive in freshwater in excess of one month, these bacteria are destroyed within 20 hours in 20 % brackish water (Chang, 1948, cited in Kenzy and Ringen, 1971).

Neither the isolation of pathogenic Leptospira from pond water used in fish culture nor human cases of Leptospirosis positively shown to have resulted from exposure to fish pond water have been reported. Nevertheless, in many human cases of Leptospirosis the route of exposure is never established, and Leptospirosis as a known water-borne disease should be considered as a potential occupational disease for aquaculture pond workers. No evidence exists to support a relationship between human Leptospirosis and the consumption of pond cultured or wild caught fish.

Schistosomiasis (Bilharzia)

Schistosomiasis is a severe, debilitating, parasitic disease of man and animals. Human infection by these blood flukes is acquired through skin penetration by infective cercaria while a person is immersed in infested water. The distribution of human Schistosomiasis is correlated with specific species of

snails which are intermediate hosts for the parasite. More than 100 million people are affected with this disease in tropical and subtropical regions of the world (National Academy of Sciences, 1973).

If water harbors the appropriate snail intermediate host then contamination with human or animal wastes containing schistosome eggs constitutes a public health hazard. Prevention and control procedures include: (1) proper disposal of sewage and animal wastes, (2) snail control, and (3) prevention of contact with cercaria-infested waters (protective clothing or non-entry). Snail control methods employed are as follows: (1) Removal of grass growing in the pond using ducks or grass carp to reduce habitat suitable for snails (Pruginin and Lipshitz, 1957). (2) Stocking species of fish that feed on molluscs to reduce snail populations. Appropriate fish species include Black carp (Mylopharyngodon piceus), African lung fish (Protopterus sp.), and the Cichlids Serranochromis macrocephala, Haplochromis mellandi, H. bimaculatus, and Astatereochromis alluaudi (Hickling, 1962). (3) Periodic draining and drying out of the pond in conjunction with the application of liming. (4) Prevention of pond contamination by human and animal feces and urine containing schistosome ova (sanitation).

Malaria

Fish ponds as standing or slow-moving bodies of water may assist in the spread of malaria by providing a breeding ground for anopheline mosquitoes (Hickling, 1962). Pielou (1946, cited in Hickling, 1962) concluded from studies carried out in Northern Rhodesia that well-managed fish ponds do not significantly increase the danger from malaria. In large ponds minimum management to achieve this goal included keeping the banks clear of grasses and unshaded, while small ponds are kept unshaded, stocked with larvivorus fish, and drained immediately if left unattended (Hickling, 1962). It was mentioned that drainage ditches and other small bodies of water near the pond (or resulting from pond leakage) would have to be managed also.

Other control measures involve proper construction of ponds, with a minimum depth of two feet. Also, extensive efforts should be made to educate persons in underdeveloped countries as to the risks involving snails and malaria from standing water (Hickling, 1962).

A Special Case: Manuring

Animal waste as a natural fertilizer in fish ponds to enhance fish productivity is routinely used in many areas of the world. In recent years the dynamics of manure on pond ecosystems and fish production have been the focus of many scientific studies. The problem of public health diseases resulting from the practice of applying manure to fish ponds has received some attention (Bhattacharya and Taylor, 1975; FDA, 1977). The occurrence of infectious disease agents, drugs, and chemicals in animal wastes is well established, but it is uncertain that the practice of applying manure to ponds actually results in human disease. Reports to show this are simply lacking. Either clinical disease does not result or the data base in inadequate to make this assessment. Clearly, studies need to be undertaken to determine if a public health hazard actually exists.

RECOMMENDATIONS FOR FUTURE PROGRAMS

Disease-control programs are practiced in animal-husbandry systems because these programs result in enhanced productivity through increases in growth and survival of farmed animals. Warmwater pond aquaculture as an animal-husbandry system should benefit by increased productivity with the implementation of progressive herd health programs. The following operatives are needed to increase the level of disease control, and therefore production, in warmwater pond aquaculture systems.

Surveillance

A quantitative data base on the status of diseases in warmwater pond aquaculture systems should be established. This program could be in the form of morbidity and mortality reporting on local, regional, and larger scales. The data base would need to be continuously updated and analyzed to determine trends. Standardized animal identification methods, disease nomenclature, and disease classification would be required prerequisites.

Services and Research

To advance the level of knowledge of the diseases affecting pond aquaculture species, increases in suitably trained manpower and facilities to provide disease diagnosis and control, services, and research are needed.

Regulations

Regulatory programs to minimize the spread of infectious diseases of warmwater pond aquaculture species need to be designed and implemented.

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POND CULTURE PRACTICES

by

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Pond culture practices have generally evolved in a slow empirical manner. Improved pond operations and management will serve as a basis for increased pond productivity and the improved nutritional status in the LDCs. Direct transfer of technology from the temperate regions (i.e. United States, Europe, Israel) is not feasible because of changes in the physical and biological phenomena, socio-political environments, and the level of management skills and objectives. Increased productivity will be based on an improved understanding of the physical, chemical and biological processes in the pond. Key unknowns in pond culture practices and research needs are considered briefly in the following section. The effect of growth limiting variables on fish production and pond engineering are considered in subsequent sections.

OVERVIEW

The material presented in this section is intended to serve as an overview of pond practices and to identify critical areas where more research is needed.

Hatchery Operations

One of the major problems in pond aquaculture is the lack of adequate fry for stocking. Greater available of fry is a single factor that would result in a rapid increase in pond production in many LDCs.

Increasing the fry supply will depend on a better understanding of the reproductive biology, better techniques for the rearing of larvae and fry, and better production hatcheries. The advantages and disadvantages of regional, village, or individual hatcheries will need to be determined on an individual country basis. The adaptation of systems used for trout, salmon, or catfish may not be possible because of difference in the environmental requirements, behavior, and feeding requirements. While most of the potential culture species have been spawned under hatchery conditions, emphasis must be placed on the production aspects under varying size levels. In some areas, small scale hatcheries operated by farmers (Osborn, 1977) may be economic but in many areas, regional or national hatcheries will produce fry and distribute them to the farmers. Improved transportation methods using pure oxygen (Johnson, 1979; Cremer and Duncan, 1979; U.S. Fish and Wildlife Service, 1978) can result in a significant increase in fry survival at a moderate cost. Legal, social and political constraints to hatchery production will need to be considered in areas where local fry collection, and distribution systems exist.

Stocking Practices in Pond Fish Culture

Rational stocking procedures will depend on a knowledge of the food preference of the various species and the amount (or production) of the different types of fish food in the pond. Better information on the food preferences of fish as a function of size and location is needed. The utilization of natural foods in the ponds is central to the objectives of increased pond productivity. Supplement foods may be added to the pond, but the major source of food will be from natural sources. Better information on the estimation and prediction of standing crop and production of the various food items is needed. Emphasis should be placed on the development of rational stocking procedures for polyculture.

Feeds and Feeding Practices in Warmwater Fish Ponds

In most LDCs only supplemental feeding with locally available products will be economically feasible. The fish will obtain a significant amount of their food from natural pond production. The key problem in formulation of supplemental feeds in warmwater ponds will be the ingestion and digestion on the food. The digestion process in the tilapia and filter-feeding fish may be inherently different from trout and catfish. These differences may especially be critical when dealing with vegetable proteins, algae, and detritius. While the conduct of digestability experiments with filter-feeding fish is very different, this information will be critical to the design of cost-effective supplemental diets.

The formulation of supplemental diets for pond systems is complicated because undigested or partially digested food may be consumed by another species or form the basis for another food chain. The formulation of supplemental diets is an ecological problem rather than a purely nutritional problem. Thus, a knowledge of the various food webs is needed to assess the impact of supplemental feed in the warmwater pond.

Food preferences, feeding habits, and feeding behavior will also be important in pond feeding. Better information on the feeding processes is needed as a function of size and species.

Local processing of local feed items to increase acceptability and digestion may be desirable. Processing techniques for local input need to be within the management and economic resources of the LDCs. Transportation of local input to a central site and then back to the local pond may not be desirable or feasible. The use of animal or fish wastes will be common in the LDCs. The passage of food items through the animal or fish may be viewed as a form of processing for local items.

Digestion and Assimilation

The majority of fish nutritional research has been conducted with fish on the top fo the food chain such as rainbow trout. The mechanisms of digestion and assimilation of the filter feeding fish or herbivorous fish are not well known. This is important because the basic processes in the digestion and assimilation for these fish may be different. Tilapia nilotica digests blue-green algae by lysing the cells with low pH gastric secretions (Moriarty, 1973) rather than using digestive enzymes. While the Tilapia species may digest algae, the efficiency is lower than for animal tissue (Mironova, 1974; Panidan and Raghuraman, 1972). The optimum growth of Tilapia aurea is at a protein level of 36 percent (Davis and Stickney, 1978). Information on the digestability of foods can be used to formulate cheaper feeds using local materials.

Fertilization Practices in Warmwater Fish Ponds

Fertilization with inorganic, animal manures, or plant material is commonly used to increase production. Both type, method of application, and interval between application vary from country to country. Over-fertilization can commonly result in algal blooms and oxygen depletion problems. Improved fertilization practices will depend on a better knowledge of local water chemistry, determination of optimum nutrient levels, and development of a better understanding of the oxygen balance in the ponds.

Over-application of inorganic fertilizers can result in the precipitation or loss of much of the fertilizer. Many of these reactions can be predicted from a knowledge of the local water chemistry. Water test kits have been found to be accurate enough for management decisions for pond aquaculture in the U.S. The validity and use of these kits should be evaluated in the LDCs. The use of these kits by extension or government workers would be very helpful.

Due to changes in the water chemistry, water flow rate, and bottom sediments, the application frequency and rate will change significantly from region to region or even from pond to pond. The measurement of critical nutrient concentration during fertilization experiments may allow management of fertilization on a concentration basis rather than a gross application basis.

The application of manure and plant matter to a pond may increase the importance of bacteria and protozoa as a source of food for the fish. A better understanding of the food web in the warmwater pond will be necessary for a fundamental understanding of the fertilization process. Increased fertilization leading to increased natural food production (algae, zooplankton, bacteria, protozoa, etc.) can also result in oxygen depletion and massive mortality.

Water Quality Management Practices

For small pond operators, water quality management in the LDCs may take the form of long-term management plans rather than plans for daily or weekly management. The knowledge that the dissolved oxygen level is going to be 0.5 mg/L in the morning is of litle use to a farmer who cannot increase the flow to the pond or aerate.

In large village or commercial ponds, both aeration or pumping may be feasible. Development of low or intermediate technology pumps and aerators should be a high priority. Special emphasis should be directed toward the use of available power sources (wind, water, or animals).

Improvements in the predictive ability of pond management models will aid in the development of better stocking, fertilizationn and feeding practices. Three areas of interest are prediction of dissolved oxygen, management of alkalinity and pH, and management of the organic build up on pond bottoms.

Development of predictive DO models will be critical in highly manured and fertilized ponds. Emphasis must be placed on evaluation of the oxygen consuming and producing components (i.e. algae, bacteria, sediment). The importance of the various components may be very different in different countries or in different types of ponds. Models developed in the U.S. should not be used without experimental verification.

Alkalinity and pH prediction will be important in areas of acid-sulfate soils or in prediction of pH due to algal activity. Extreme pH values can stress the fish, but probably more importantly can greatly increase the toxicity of ammonia, nitrite, and hydrogen sulfide. At low pH, the solubility of iron, aluminum, and heavy metals is increased. The prediction of pH depends on a complete understanding of the local water and soil chemistry and buffer systems. The buffer systems in the areas of acid-sulfate soils may significantly differ from those found in the temperate regions. Better information on water chemistry will also help in the reclamation of acid-sulfate soil.

Draining and drying of the pond is a significant feature of water quality management in pond aquaculture. This allows oxidation and mineralization of the accumulated organic matter and reduction of the oxygen demand of the pond sediment. Development of better criteria for draining would be useful for pond management.

Diseases, Competitors, Pests, Predators and Public Health Considerations

Prevention of disease problems in the LDCs will be a management problem rather than a treatment problem. Primary emphasis should be placed on better culture practices and reducing stress.

Public health considerations will greatly influence the use of aquaculture to increase food production in the LDCs. This includes diseases of

animals that are transmitted to man and diseases of man whose prevalence is increased through aquaculture activities. Major effort will be needed to monitor the impact of aquaculture on public health. The impact of pond fertilization with human wastes needs careful study.

Harvesting

Improvements in harvesting will have little effect on the productivity of ponds. In subsistence ponds, labor intensive harvesting using either modern nets or locally produced nets is adequate. In many areas, the use of better harvesting techniques may not be economic because of the lack of transportation or processing facilities. In large production ponds mechanical harvesting, grading, loading, and hauling techniques may be useful (Greenland, 1974). The use of traps for some species of fish should be investigated (Greenland and Gill, 1974a, 1974b).

Pond Engineering

The technology required for pond engineering is well-defined and available at the present time. The significant problem facing the LDCs is the application of technology within the technical, social, political, and legal structure of the country. Innovative engineering will be required to provide simple but effective solutions. Pond engineering is considered further in a subsequent section.

EFFECT OF GROWTH LIMITING VARIABLES ON FISH PRODUCTION

The growth and production of fish in a pond culture system will depend on complex interactions of physical, chemical, and biological parameters. The major fish species that have potential for pond culture in LDCs are listed in Table 1. Local species may also have potential or have a high market value. In many areas, the main emphasis of aquaculture will be the production of high priced products for the export market (Kutty, 1980). Freshwater and marine shrimp salmon, trout, and eels would be important species in this group.

The species listed in Table 1 feed low on the food chain or are omnivores. These fish are also very hardy and can survive a wide range of environmental conditions. The scientific data base on these species ranges from excellent to none. Also, much of the published literature on the silver and bighead carp is in Russian, Chinese, or East European languages. FAO (Rosa, 1965) has prepared reviews of some of the species, but these reports are not routinely updated nor easily available. Excellent reviews are available for the Tilapia (ICLARM, 1980; Barlin, 1979; Colt et al., 1979), common carp (Colt et al., 1979), and mullet (De Silva, 1980). For other species such as the Chinese carp, very little is known or available.

To develop pond aquaculture on a rational basis, the effects of physical, chemical, and biological parameters must be available to the researchers prior to the start of research. Emphasis must be placed on the synthesis of the data, rather than fancy computer techniques. A preliminary outline of the topics of interest is presented in Table 2. This list

Table 1

POTENTIAL SPECIES FOR POND CULTURE

Common name	Scientific name
Common Carp	*Cyprinus carpio*
Grass Carp	*Ctenopharyngodon idellus*
Silver Carp	*Hypothalmichthys molitrix*
Big Head Carp	*Aristichthys nobilis*
Mud Carp	*Cirrhina molitorella*
Snail Carp	*Mylopharyngodon piceus*
Walking Catfish	*Clarias lazera*
	Clarias fuscus
	Clarias betrachus
Thai Catfish	*Pangasius sutchi*
	Pangasius larnaudi
Java Tilapia	*Sarotherodon mossambica*
Nile Tilapia	*Sarotherodon nilotica*
	Sarotherodon aurea
Zill's Tilapia	*Tilapia zilli*
Grey Mullet	*Mugil cephalus*
Milkfish	*Chanos chanos*
Tambaqui	*Colossoma macropomum*
Pirapitinga	*Colossoma bidens*

is based on experience in the temperate zone, so other parameters may be added as data becomes available. Documentation of the effects of key variables on the growth and production of the important species is necessary. This can best be done at a central site. This center could also be responsible for custom literature searches and supplying researchers in the field with needed articles and reports. The key purpose of preparing literature reviews and data synthesis is the identification of key gaps in the data.

There are two critical areas that limit fish production in ponds:

1. the effects of ammonia, nitrite, nitrate, dissolved oxygen, hydrogen sulfide, and pH on the growth and mortality of fish
2. control of the reproduction and early larval development of fishes

A better understanding in these two areas will have a significant effect on increasing pond production. The importance of these areas will be discussed in more detail.

Table 2

PARAMETERS OF INTEREST IN POND CULTURE SYSTEMS

Physical	Chemical	Biological	Metabolic wastes
Temperature	Dissolved Gases		
Light Intensity	Oxygen	Feeding Habits	
	Carbon Dioxide		Ammonia
Photoperiod	Hydrogen Sulfide	Digestion and Assimilation	Nitrite
Sound		Growth	Nitrate
Water Depth/Pond Size	Dissolved Gas Supersaturation	Off-Flavor	Fecal Wastes
	Salinity	Ecology	Bacteria
	Heavy Metals	Reproduction	Solids
	pH	Disease	Phenomones
	Biocides	Predation	

Ammonia, Nitrite, Nitrate, Dissolved Oxygen, Hydrogen Sulfide, and pH

Better information on the effects of these parameters in the growth and mortality will be necessary for the development of both research growth models and the management plans. These parameters are critical in ponds receiving animal manures and waste products. The over-fertilization of ponds can result in low dissolved oxygen, and high ammonia and hydrogen sulfide at the same time (Boyd et al., 1979; Hollerman and Boyd, 1980).

Ammonia Dissolved ammonia gas is a weak base, the equilibrium expression for this reaction can be written as:

$$NH_3 + H_2O \quad NH_4^+ + OH^-$$

The un-ionized ammonia (NH_3) is the toxic form. The concentration of un-ionized ammonia depends on pH, temperature, and salinity. The source of ammonia in ponds is ammonia excretion of fish and the addition of fertilizers and manures. High temperatures and pH favor the un-ionized form. In water with low alkalinity, the removal of inorganic carbon by algae can produce pH in excess of 10.0. As the ammonia level of the ambient water increases, the ammonia excretion of most aquatic animals decreases and the ammonia level in the blood and tissue increases. The lethal levels of un-ionized ammonia range from 0.4 mg/L NH_3-N for trout to 3.0 mg/L NH_3-N for channel catfish (Colt and Armstrong, 1981). Un-ionized ammonia reduces the growth of channel catfish in a linear manner over the range of .048 to 1.00 mg/L NH_3-N (Colt et al., 1978). At least for channel catfish, there does not appear to be a "no effects" level for un-ionized ammonia. Except for work on the lethal tolerance of Tilapia (Redner and Stickney, 1979) and the common carp (Flis, 1968a,b), little is known about the effects of ammonia on the species listed in Table 1. Information on both the effects of ammonia on mortality and growth is needed. The effect of daily increases in pH and un-ionized levels must be determined. Fluctuating un-ionized ammonia concentrations are more toxic than exposure to a constant value equal to the mean of fluctuating concentrations (Thurston et al., 1981a). The effects of fluctuating ammonia concentration on the growth of fish are unknown. It is unknown if the peak un-ionized ammonia level, the mean un-ionized ammonia level, or some combination of the two would be the best predictor of growth reduction. Ammonia toxicity is increased at low dissolved oxygen (Thurston et al., 1981b). Therefore, the joint toxicity of these two parameters will be more important than the effects of the individual parameters. Ammonia toxicity may be a key parameter for the determination of fertilizer and manure application rates because both high un-ionized ammonia concentrations and low dissolved oxygen levels may be produced.

Nitrite Under aerobic conditions, nitrite is commonly produced by nitrification of ammonia. Nitrite is the ionized form of nitrous acid, a weak acid. This reaction can be written as

$$HNO_2 \quad H^+ + NO_2^-$$

The toxicity of nitrite may be due to the nitrous acid concentration (Colt et al., 1981; Russo et al., 1981). The nitrous acid level depends on temperature, pH, and salinity. Low pH and temperature favor the formation of nitrous acid. The major effect of nitrite (or nitrous acid) is the oxidation of the iron in the hemoglobin molecule from Fe^{+2} to Fe^{+++} (Colt and Armstrong, 1981). Since the oxidized form of hemoglobin is unable to act as an oxygen carrier, if sufficient ferrihemoglobin is formed, hypoxia and cyanosis may result. The toxicity of nitrite (or nitrous acid) will be greatly increased at low dissolved oxygen levels and high temperatures. Except for rainbow trout and channel catfish little is known about the effect of nitrite on fish (Colt et al., 1981, Colt and Armstrong, 1981). The growth of channel catfish was reduced at 1.60 mg/L NO_2^--N and above (Colt et al., 1981). Information on the effects of constant and fluctuating levels of nitrous acids on both growth and mortality is needed. This information may prove critical in areas of acid sulfate soil where very low

pH may be present. Because of the interaction with dissolved oxygen, the joint toxicity of these parameters will need to be investigated.

Nitrate Nitrate levels may build up in ponds from the nitrification of ammonia. Nitrates can be considered completely dissociated and have very little toxicity to aquatic animals. Under anaerobic conditions, the reduction of nitrate to nitrite may occur. Also, under some conditions, algae may produce high levels of nitrite (Kinne, 1977).

Dissolved Oxygen Dissolved oxygen is a key parameter that may limit production or result in high mortality in ponds. The lethal dissolved oxygen for fish ranges from 2 to 3 mg/L for trout and salmon and 0.5 to 1.0 mg/L for warmwater fish. The growth of several species of fish is reduced when the dissolved oxygen is less than 5 mg/L (Brett and Blackburn, 1981). Dissolved oxygen levels in ponds typically are supersaturated in the afternoon and decrease during the night (Hollerman and Boyd, 1980). The effects of these fluctuations on mortality and growth are critical to development of pond management models. As discussed in the previous section, dissolved oxygen can greatly increase the toxicity of ammonia and nitrite. Therefore, the joint toxicity of dissolved oxygen + ammonia and dissolved oxygen + nitrite are the key parameters to be studied.

Hydrogen Sulfide Hydrogen sulfide (H_2S) may be produced on the pond bottoms by anaerobic bacteria. Mass mortality of fish may result if the pond water is mixed. The concentration of H_2S depends on the pH, temperature, and salinty. Low pHs favor H_2S. Lethal H_2S levels range from 0.8 mg/L for channel catfish (Bonn and Follis, 1967) to 0.008 mg/L for trout (Reynolds and Haines, 1980). H_2S levels above 2.0 mg/L have been measured in ponds (Bonn and Follis, 1967). The toxic effect of H_2S may be due to interference with enzyme action or to mitochondrial changes (Smith and Oseid, 1974).

The accumulation of organic matter on the pond bottom or the failure to remove vegetation before filling the pond may result in anaerobic conditions and the production of H_2S. Data on the effects of H_2S on the growth and mortality of those species that may be raised in areas of low pH or in manured ponds is needed.

pH For short periods of time, fish may be able to tolerate pH values ranging from 3.5 to 10.5 (Haines, 1981, Colt et al., 1979). Over the range of 6 to 9, pH may have little effect on fish. At a chronic low pH, reproduction and normal larval development are prevented (Haines, 1981). Low pH increases the toxicity of nitrite and hydrogen sulfide, while high pHs increase the toxicity of ammonia. Therefore, the major effect of pH may be to influence the concentration of the weak acids and bases and the solubility of iron and aluminum compounds (Singh, 1980). The joint toxicity of these parameters with a constant or diurnally fluctuating pH concentration needs to be defined.

Control of Reproduction

The lack of adequate fry is a major problem in pond culture in many parts of the world and therefore is a key topic in increasing pond production (Kutty, 1980). Emphasis must be placed on both controlled reproduction, the early growth of the fry, and production hatchery techniques. The control of over-breeding by the tilapia species should be investigated by the use of androgens (Anderson and Smitherman, 1978; Guerrero, 1975), sterile hybrids (Pruginin et al., 1975) or local predators. Technological control of over-breeding of tilapia is of little use if the techniques can not be used by the LDCs. The implementation of technology into the LDCs is a critical issue that needs to be addressed in research planning.

POND ENGINEERING

The design of ponds for aquaculture depends on information from a large number of fields including meteorology, hydrology, hydraulics, soil mechanics, civil engineering, and biology. The technology required for the engineering, construction, and management of ponds is well-defined and available at the present time. The significant problem facing the LDCs is the application of technology within the technical, social, political and legal structure of the country. Therefore, pond engineering practices will vary from country and the size (or scale) of operation. In subsistence ponds, improved pond engineering may have little impact. In the large-scale commercial pond systems, the level of engineering will be similar to Israel, Taiwan, or the southern United States. Improvements in pond engineering in the small-scale commercial or village ponds will have the greatest potential to increase pond production, but will require the most innovative engineering. Emphasis must be placed on intermediate technology that is both simple and effective.

Pond engineering will be discussed in terms of pond design, pond construction, pond maintenance, and pond operation. Areas of research will be discussed in each section. Emphasis will be placed on areas where research can improve engineering practices and increase production.

Design of Ponds and Other Facilities

Pond design includes not only the design of the pond itself, but the water collection system, water conveyance system, water control structure and the hatchery facilities.

Water Source The most common source of water will be surface streams or tidal water. The salinity, temperature, or silt load may vary significantly due to high winds, rain, or flooding. This water may also contain adults, larvae, or eggs of undesirable predators.

In Central America, South America, or Africa (Lovshin, 1980; Grover et al., 1980; Huet, 1971), a small dam is constructed and part of the stream flow is diverted into the pond. The water flows to the pond by gravity. During high flow conditions, the major water flow passes over the dam. The pond should be circled by a ditch to intercept surface runoff and prevent excessive flow to the pond.

In Indonesia brackish water ponds are typically sited so that the ponds are filled during high tides and emptied during low tides. The source of water is from tidal streams or the ocean. Therefore, the

siting and operation depend on the tidal cycle. The water level within the main levee is controlled by a series of secondary gates.

For large pond systems, it may be necessary to measure streamflow or estimate water yield from precipitation data. The diversion dams can be designed with local contractors using simple methods (Soil Conservation Service, 1971).

The use of gravity flow systems offers a simple, cheap, and reliable method for ponds constructed in a suitable site. This requirement for brackish water farm may require that the ponds be located in areas that may be subject to frequent flooding or storm surge damage. The use of pumps may allow greater flexibility in the siting of brackish water ponds. The use of low head/high volume pumps for aquaculture should be investigated. Axial flow (Jamande, 1977), hydraulic pumps (Jamande, 1977), or low technology pumps (Tamiyavanish, 1977; Watt, 1976) may be used. The use of windmills may be economic in areas with adequate wind energy (Tamiyavanich, 1977; Fraenkel, 1975). The economics of electrical or gasoline pumps must be carefully formulated to reflect the cost of bringing the power to the pond, availability of spare parts, and availability of people to repair these pumps. A proper analysis may find that low technology pumps with low efficiencies may be more economic than modern pumps.

Because of the variation in water quality of surface water, this source may be unacceptable without pretreatment for hatchery systems. Drilled wells or subsand wells (Scholes, 1980) may be required. Because of the impact of the loss of the water supply, gravity reservoirs or standby generator may be necessary for hatcheries.

Distribution System Unlined ditches are the most common method for water conveyance. In large projects, the design should be based on standard hydraulic practices (Aisenbrey et al., 1978; Kraatz and Mahajan, 1975a, 1975b). Because of low cost and ease of installation, the use of PVC pipe should be investigated. The design of water conveyance systems is simple and within the technical ability of the LDCs.

Water Pretreatment In coastal fish farms, the introduction of predators or trash fish into the pond is a serious problem. These fish may be introduced as adults, larvae or eggs and may directly feed on the cultured fish, compete for food, or have low market value. Multiple bamboo screens are installed on the main gate (Yamashita and Sutardjo, 1977). Because of the importance of preventing the induction of predators the use of more durable plastic or plastic-coated mesh may be economic. In ponds where the water is introduced into the pond from a ditch or pipe, the saran box filter or saran sock filter could be used (Fish and Wildlife Service, 1973).

In hatcheries, the removal of silt, suspended matter, and parasites is required (Osborn, 1977; Cook, 1977). Modern pressure filter of the mixed media type should be investigated for large-scale regional hatcheries. The development of better hatchery system is a high priority.

Water Control Structures The water level in ponds is controlled by overflow devices of the "monk" (Huet, 1971) or the turn-down drain pipe type (Stickney, 1979). The turn-down type is superior to the monk both in ease of construction and use. The pond bank under the inlet pipe should be riprapped or concreted to prevent erosion.

In brackish water farm ponds, the main and secondary gates are major structures up to 1.5 m wide (Tang, 1977). The water level is controlled by stop logs. The main gate is constructed from concrete or wood depending on local practices and the bearing strength of the soil. The design and operation of this unit is straightforward.

Levees The design of levees for ponds depends on the desired depth of the water, the probability of overtopping due to flooding and the hydraulic and physical characteristics of the levee material.

In areas with a long history of fish culture, the design of pond has evolved in an empirical manner and may represent an optimum for the local management skills and practices. In other areas where pond design has been adapted from other areas, there may be more potential for increased production and efficiency. In any case, the local design should be used as a starting point.

Pond depths typically range from 30 to 200 cm (Tang, 1979; Hickling, 1971). The optimum pond depth may be determined by complex interaction between the requirements of the fish and principal food organisms. For tidal milkfish culture some of the factors influencing pond depth are listed in Table 3. Because of the complexities of the effect of pond depth on product, the design depth in most regions is based on experience. Rational selection of depth will be based on growth models for both the food and fish, the energy balance (Szumiec, 1979) and dissolved oxygen (Romaire and Boyd, 1979; Boyd et al., 1978). Separate ponds for the food and fish and artificial support for the benthic algae (Crance and Leary, 1979) could be used to increase production, but require a higher level of management.

The design of the levees depends strongly on the local characteristics of the soil. Therefore, the design may vary from country to country and within a country. If available, the levee should be constructed from an impermeable clay or with a clay core (Tang, 1979; Hechanova, 1977). The bottom of the cut-off trench or clay core must be extended through the top soil (Cremer and Duncan, 1979). The use of plastic films (such as Hypalon or butyl rubber) or bentonite clay to reduce seepage should be investigated. Improved testing procedures must be developed to determine the suitability of soil for levee construction especially with regard to acid-sulfate soils. In exposed coastal areas, research on the use of breakwaters or natural buffer zones is needed to prevent erosion. The use of pumps in coastal areas may allow construction of ponds away from the near tidal areas where erosion and acid-sulfate soil are common.

Pond Size and Orientation Pond size typically ranges from 0.1 to 2.0 ha. Pond size depends on the availability of land, harvesting and operational flexibility. Nursery ponds for milkfish or Chinese carp (Korringa, 1977; Hickling, 1971) may be only 10-50 m^2. Production ponds for milkfish ranges from 4 to 6 ha. Ponds of rectangular shape are more convenient to harvest (Tang, 1979). Their long sides should be aligned perpendicular to the prevailing winds to reduce wind

Table 3

FACTORS INFLUENCING THE OPTIMUM POND DEPTH IN MILKFISH PONDS

Factor	Problem	Reference
Depth	Optimum depth for benthic algae is 10-15 cm	Korringa, 1976
	Older fish will not enter shallow water, ponds must be > 30 cm	Korringa, 1976
	Self shading by algae may limit the useful depth of the ponds	Szumiec, 1979
	Increased depth may produce undesirable anaerobic bottom conditions	Korringa, 1976
Temperature	Shelter trenches required for fish	Huet, 1972
Salinity	High salinity has serious effect on benthic algae, but not the fish	Tang, 1979; Korringa, 1976
Productivity	Heavy organic fertilization may increase the production of non-photosynthetic organisms	Moav et al., 1977

induced bank erosion. Larger sized ponds are cheaper to build, but small ponds are cheaper to maintain and more convenient to manage.

Siting of Ponds In coastal areas (Tang, 1979) the siting of ponds will depend on 1) ground elevation and tidal range, 2) soil type, and 3) type and density of vegetation. The use of mangrove swamps may be restricted due to environmental concerns and erosion problems (Gatus and Martinez, 1977; Thompson and Tai, 1977). Also, uncontrolled pond construction may increase flooding and sedimentation problems (Guanzon and Basa, 1977). Pesticide pollution may be a major constraint in some areas (Rudayat and Oetomo, 1977). In many areas, flooding and loss of fish is a serious problem. This flooding may occur due to heavy rains or more commonly due to large tropical storms that result in high tides and winds. A methodology for risk/benefit analysis is needed as a management tool.

The procedure for the siting of coastal ponds is well developed (Tang, 1979; Hechanova, 1977). The use of pumps or aeration may allow siting of ponds in areas that are presently unsuitable.

In tropical Asia there are 13 million hectares of acid-sulfate soils that could be developed for aquaculture (Singh, 1980). The reclamation of these areas requires periodic drying and flushing to oxidize the pyrite and leach the acidity and fertilization with lime and manure (Singh, 1980). This process may require 3 to 4 years. Improved techniques for both the assessment of the acid producing potential of a soil and reclamation of acid sulfate soils may allow development of large areas of unused land.

In non-coastal areas (Maar et al., 1966), the siting of ponds will depend on 1) a source of surface water, 2) soil type, and 3) topography. It is desirable that the ponds can be drained by gravity. In larger ponds systems, the use of pumps may be economic and useful.

Pond Construction

The construction of ponds and associated structures is a well developed art in most LDC. Construction methods may range from manual methods (Denila, 1977) to modern capital intensive methods (Aquaculture Planning in Africa, 1975). Several excellent construction manuals for manual and modern methods are available (Soil Conservation Service, 1971; Moav et al., 1966; Charkroff, 1976). In some cases, mechanical methods are unsuitable for use in coastal areas because of the low bearing strength of the soil (Lijauco, 1977).

The choice of construction method will depend strongly on local conditions including the availability of labor and capital, political constraints, time requirement, and the method of economic analysis. Mechanically intensive methods tend to be cheaper, of better quality and faster than manual methods (Tang, 1977). The manual method will generate local employment and save foreign exchange. The impact of increasing local employment has not been adequately evaluated in relationship to the overall economics of the construction methods.

Pond Maintenance

Important aspects of pond maintenance include levee stabilization, predator control, and weed control. Pond maintenance problems are more serious in the coastal zone. Pond maintenance will require daily or weekly inspection of levees and the water system.

Maintenance of ponds will require adjustment of water flow, checking inlet and outlet structures, and checking for leaks. In milkfish culture, leakage and stabilization problems may prevent the stocking of fish until 3 to 4 years after construction. Levee stabilization may be improved by planting of grasses or trees on the levee (Freshwater Fisheries and Aquaculture in China, 1977; Comacho, 1977; Korringa, 1976). Species include mangroves, mulberry, or Bermuda grass. Bermuda grass shows promise in the stabilization of acid sulfate soil, a serious problem in some coastal areas. In most areas, pond control of both predator fish and terrestrial predators such as otter, herons, frogs, and snakes can prevent significant loss of fish. Screens will have to be checked to prevent entry of predator fish. Draining and drying of ponds will be required to kill predators prior to stocking. Because some tropical fish can burrow into the mud and survive, pond may need to be dried and filled several times. Grass and trees on the levees will have to be trimmed to avoid hiding places for snakes and other predators. Birds and otters can be controlled by guns. Weed control in the ponds may depend on proper construction, manual removal, or stocking with herbivorous fish.

Pond Operation and Management

Improved pond operations and management plans will form the basis for improved production in ponds. For subsistence ponds, pond management plans need to be formulated in terms that the operators can understand and use. While these plans will not be optimum, they should be optimum in terms of the management level available.

In the larger ponds, the management plan can be more sophisticated to reflect both the increase in management skills and management tools. Water test kits (Boyd, 1980; Boyd, 1977) are adequate for management decisions, although their use in tropical areas should be evaluated. The monitoring as well as the use of aeration systems and pumping will allow significant improvements in production. Development of predictive water quality management models (Boyd and Lichtkoppler, 1979; Boyd, 1979; Boyd et al., 1978; Romarie and Boyd, 1979) should be developed for the tropics.

Most pond management practices such as liming, fertilization, manuring or draining and drying have developed from empirical growth trials using fish production as the figure of merit. The formulation management plans on a more fundamental basis (i.e., maintenance of total hardness $\geq$20 mg/L rather than addition of 1000 kg/ha·y) may offer significant cost savings to the larger operations. Development of rational management criteria will also aid in the selection of local materials (i.e., hog manure versus cow manure).

Integrated fish culture and animal production will allow increased efficiency reduced fertilization costs (Pullin and Shehadeh, 1980). In the subsistence ponds, the animal will be housed over the ponds or upslope from the pond. In larger ponds, the manure will be collected and distributed to the ponds. This may allow higher levels of production and flexibility.

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PART 4

MODELLING OF POND AQUACULTURE SYSTEMS

MODELING THE HYDROMECHANICAL AND WATER QUALITY RESPONSES OF AQUACULTURE PONDS

A Literature Review

by

Nikola Marjanovic and Gerald T. Orlob

INTRODUCTION

Background

Development of a quantitative methodology for the assessment of aquaculture pond performance and design suggests the need for a suitable mathematical model. Such a model should have the capability for simulation of the important characteristics of pond dynamics that influence overall protein production, i.e., fish biomass. Hence, the model might be expected to include hydrodynamic behavior, water quality-ecological interactions, chemical-biochemical kinetics and certain environmental factors that determine ecologic response at the trophic level of prime concern.

Such models, dealing at least in part with these notions and principles, are known to exist, although few are apparent that are readily transferable to the case of pond aquaculture. As a point of beginning, it was determined that a careful review of the state-of-the-art of modeling, specifically directed to ponds, and small lakes or reservoirs that might resemble ponds in scale at least, should be conducted. This report is the result of such a review.

Scope of Review

An earlier review of mathematical modeling of surface water impoundments [Orlob, 1977] conducted for the Office of Water Research and Technology (OWRT) Department of the Interior provided a substantial foundation for the present undertaking. It included more than 400 references, dealing with the broader subject area, i.e., impoundments, and a digest of 90 specific models of impoundments that were considered to be at a level of development and documentation adequate for transfer of modeling technology. Among these were included the models most widely used by the major water agencies in the United States, e.g., Corps of Engineers, Environmental Protection Agency, Bureau of Reclamation, etc., to evaluate environmental impacts of water development and pollution control projects. In addition, models of more specialized scope, such as those of the International Biological Program were referenced and documented.

Notwithstanding the scope of this earlier effort, it did not focus sufficiently on the smaller water bodies, such as aquaculture ponds, and it did not treat questions of primary concern in the present research. Specifically, it did not address questions directed to enhancement of the productivity of ponds designed to generate a harvestable reservoir of protein.

It was decided to examine in depth the extant published literature dealing with a selected list of topics which would encompass all aspects of pond technology relevant to construction of a mathematical model, or models, of an aquaculture system. The following topics were identified:

- Hydromechanics of ponds, small lakes and reservoirs, including wind induced circulation, thermal effects, stratification and destratification, turbulence and mixing and artificial circulation systems.
- Water quality, including temperature, dissolved oxygen, BOD, chemical constituents, abiotic nutrients, toxics, sediment, etc.
- Ecological interactions, including biota at all trophic levels, bacteria through nekton, kinetics of growth, respiration, nutrient limitation, toxicity, photosynthesis, predation and resilience.
- Model development, including models specifically concerned with hydromechanics, water quality, or ecology of ponds, or combinations of these, noting degree of transferability and documentation.

The review was designed to cover at least the most recent 10 years of publication in selected scientific media, although through cross referencing and tracing of cited references, the chronological scope was inevitably extended. Also, certain limited circulation documents, notably project reports, which were found in the earlier review [Orlob, 1977] to be prime sources of "working" models, were carefully reviewed when accessible.

The major journals covered in the present review included but were not limited to the following.

1) Water Resources Research
2) Journal of Water Pollution Control Federation
3) Journal of Hydrology
4) American Society of Civil Engineers:
   - Journal of Hydraulic Division
   - Journal of Irrigation and Drainage Division
   - Journal of Environmental Engineering Division
5) Transaction of the American Fishery Society
6) Hydrobiologia
7) Journal of Limnology and Oceanography
8) Journal of Ecology
9) Journal of Environmental Quality
10) Aquaculture

Execution of Literature Search and Review

The search of the literature was carried out over the period February through April 1981. It resulted in some 230 individual references dealing with the topics cited above. Among these about 180 were considered worthy of citation in the annotated review which comprises Chapter III of this report. Abstracts were secured or prepared for each literature source cited.

The literature search was carried out by N. Marjanović under the direction of G. T. Orlob, principal investigator for the project. Abstracting and the first draft of the annotated review were the responsibility of Mr. Marjanović. The report was edited and summarized by Professor Orlob. Typing of the manuscript was entrusted to the secretarial staff of the Department of Civil Engineering.

The project report constitutes an interim submittal for the research project under contract between the Regents of the University of California and Oregon State University. Chapter II following is a summary of project findings and conclusions. Chapter III is an annotated literature review. Chapter IV presents a discussion of findings and conclusions. Appendix A is a list of references cited.

SUMMARY

A review of literature was perfomed to determine the state of research and development related to mathematical modeling of aquaculture ponds with specific reference to hydromechanical and water quality responses. The review covered publications during the most recent 10 years in selected scientific media plus documents of limited circulation, e.g., reports and computer programs that were identified in the search.

An annotated review of the literature most relevant to mathematical modeling of aquaculture systems includes some 180 references. This review is presented in four major sections dealing with 1) General Ecologic - Water Quality Publications, 2) Hydraulics and Hydromechanics, 3) Water Quality and 4) Models of Aquatic Systems.

General Ecology - Water Quality

General literature sources provide useful background for model development, but comparatively little that specifically deals with the quantitative aspects of aquaculture. The classical treatise of Hutchinson [1957] and the textbook by Wetzel [1975] are among the most useful. Textbooks and monographs which provide specific examples of models - usually of lakes or reservoirs - that are analogous to pond systems are useful in guiding future model development. For example, an excellent review of mixing and circulation processes in natural water bodies is found in Fischer, et al. [1979], which also includes a detailed description of a unique one-dimensional reservoir model, DYRESM [Imberger, et al., [1977], that may be useful in pond modeling.

Temperature effects on impoundments, including major heat exchange processes represented in quantitative form, are thoroughly reviewed in a report by the TVA Engineering Laboratory [1974]. Physico-chemistry of stratified lakes and reservoirs has been modeled with some success, and extension of the classical BOD-DO relationships to pond systems appears practical. However, such models do not integrate water quality and aquatic ecology, i.e., they are not comprehensive. Nutrient balances and limitations have been subjects of much research and in a few instances have been utilized with some success in ecological model building [Chen and Orlob, 1975; DiToro et al., 1975; Park, et al., 1976]. However, there are few references which deal with water quality - ecological interactions at a level of detail suitable for structuring of an aquaculture pond model.

Hydraulics and Hydromechanics

Published literature relevant to the hydromechanics of ponds or pond systems is virtually non-existent. The developer of aquaculture pond models will have to draw on experience with modeling of larger water bodies, even though this may not be particularly fruitful. The earliest lake and reservoir models, for example, were usually one-dimensional, applied to highly stratified systems. They considered only the most rudimentary hydromechanical principles. Subsequent development in hydrodynamic modeling appears to have been focused on very large lakes, such as the Great Lakes, where circulations are induced by a combination of wind stress at the surface and convective mixing induced by seasonal and diurnal thermal cycles. Mixing processes in such systems were generally treated empirically from the modeling viewpoint, coefficients of "effective diffusion" being derived from observation on actual lakes and reservoirs.

The state-of-the-art of modeling wind-driven circulation in large lakes is probably best represented by the models of Simons [1973] and Simons et al. [1977]. Two dimensional models of stratified flows, common in both natural and man-made impoundments, are exemplified by the work of King and Norton [1975] and Edinger and Buchak [1975]. While these experiences are useful in the general sense of hydrodynamic modeling, they provide little that is directly transferable to design of pond systems. The most promising research identified in this review, in terms of applicability to ponds, may well be that concerned with small-scale wind-mixing effects in the epilimnion [Stefan et al. 1976]. Otherwise, the hydromechanics literature is non-specific as regards the particular kinds of problems likely to be encountered in design of a pond model.

Water Quality

The thermal behavior of lakes and reservoirs has been a subject of considerable research and some excellent models exist for prediction of temperature changes and calculation of heat energy transfer [WRE, 1968; Huber, et al., 1972; TVA, 1974]. Pond temperature regimes have been well characterized for both temperate and tropical climates [Young, 1975] and effects on fish have been investigated under a wide variety of conditions.

Effects of low dissolved oxygen on fish in ponds have been analyzed in a series of well executed experiments on catfish ponds [Tucker and Boyd, 1977; Tucker, et al., 1979; Romaire and Boyd, 1979; Hollerman and Boyd, 1980]. A model was developed to estimate DO fluctuations in ponds over a diurnal cycle due to photosynthesis and respiration by plankton, fish and benthic communities. Experiments were performed on methods of raising DO.

Chemical characteristics of ponds in relation to physical and biological properties are not well documented in the extant literature. On the other hand, considerable information is available in toxic effects of heavy metals, chlorine, ozone, etc. on fish [Cairns, et al., 1975; Katz, 1977], including behavioral responses to pollutants [Tarrick, et al., 1978; Morgan, 1979]. Usually, these experiments have been under closely controlled conditions in the laboratory; few have been performed in actual ponds.

Modeling of Aquatic Systems

The stimulus for development of mathematical models of aquatic systems came largely from pollution control efforts in the United States during the 1960's. Simple gross nutrient budget models were first devised to evaluate eutrophication control strategies for lakes [Vollenweider, 1969; Snodgrass and O'Melia, 1975; Larsen and Mercier, 1975]. These were complemented subsequently by more descriptive models, that attempted to include important water quality - ecological interactions. The development of these descriptive models began with one-dimensional representations of stratified impoundments, either lakes or reservoirs, with thermal structure as the primary concern [WRE, 1968; Huber et al., 1972; Baca and Arnett, 1976]. Once a capability to model temperature changes in simple impoundments was achieved, other water quality and ecological phenomena were added [Chen, 1968; Markovsky and Harleman, 1973]. A versatile water quality - ecological model known as LAKECO was developed for the Environmental Protection Agency [Chen and Orlob, 1975]. This model, in one-dimensional form, was capable of simulating 20 or more water quality and biological state variables to characterize their temporal and spatial distributions in reservoirs and lakes under realistic environmental and operating conditions. It was, however, a one-dimensional model.

The limitations of the one-dimensional representation for ecological models were examined by Ford and Thornton [1979], who noted that the characteristic time scales of hydrodynamic, chemical and biological phenomena dictate upper and lower bounds for which the one-dimensional approximation is acceptable. Later the concepts of LAKECO were incorporated in WQRRS, a comprehensive river-reservoir model of the Corps of Engineers. It extended to three dimensions by Chen, et al. [1975] for simulation of large lakes. Similar models were developed by DiToro et al. [1975] and Thomann, et al. [1973, 1974, 1975].

An important modeling effort with stronger emphasis on biological aspects was initiated in the International Biological Program by a group at Rensselaer Polytechnic Institute [Park, et al., 1976]. It resulted in a series of multi-compartment models, CLEAN, CLEANER, MS. CLEANER, etc. [Youngberg,-1977; Desormeau, 1978; Leung, 1978], which have been applied to a wide variety of situations in the United States and Europe. The careful biological structuring of these models places them in a leading position, along with recent versions of LAKECO, as the most promising foundations for development of an aquaculture pond model.

Concluding Comment

A review of the literature reveals some large gaps in the science and technology needed for development of a mathematical model that can be used to aid in the design of aquaculture ponds. The greatest deficiencies are in the lack of comprehensiveness of available models. This is found in failure to deal with the complete ecosystem (not just specific species), neglect of hydromechanical factors, and lack of attention to the interaction of water quality constituents and biota of the pond system. The relationship between the aerobic, facultative and anaerobic zones in an aquaculture pond has not been adequately studied, at least from a modeling viewpoint.

It appears that mathematical modeling of aquaculture pond systems is a potentially fruitful area of research that could yield useful tools for enhancing the overall productivity of such systems. Such models, if they can be developed, would surely improve design of ponds, facilitate structuring of field demonstration and data programs and generally contribute to better understanding of the behavior of aquaculture systems.

ANNOTATED LITERATURE REVIEW

This chapter presents the findings of the literature review in the form of an annotated narrative. The review is highlighted by specific references to publications that are considered important background for development of a modeling capability. An effort has been made to cite directly the majority of relevant works although it is recognized that some may have inadvertently overlooked.

The review is organized in four sections. The first deals with publications of general interest in the fields of ecology and water quality, usually books, monographs or treatises. In the second section, we review hydraulics and hydromechanics of ponds, small lakes, and reservoirs. The third section covers water quality and the fourth deals with ecosystems. Emphasis in all sections is on models and modeling techniques and the feasibility of development of an aquaculture pond model or models.

General Ecologic-Water Quality Publications

All publications dealing with aquatic ecosystems in general, or to larger water bodies, such as lakes and big reservoirs, but which can be useful in analyzing small lakes, ponds and reservoirs, and in constructing models of such water bodies, are classified in this group.

General Ecology, Limnology and Water Quality There are a few important books dealing with general limnology and ecology of fresh waters which contain information useful in model development. Among the more notable are the treatise on limnology by Hutchinson [1957] and the textbook by Wetzel [1975]. There is some tendency in these and other general works to treat the study of inland waters with specific regard to geographic conditions or as unique case studies. However, such references provide useful comprehensive and up-to-date accounts of the physical, chemical and biological processes operating in inland waters (or particular parts of them), very often with emphasis on their ecologic effects [Bayly and Williams, 1973; Reid and Wood, 1976; Aleyev, 1977].

Also, there is a formidable body of information on the effects of man on ecosystems, especially on the environmental impact of thermal electric power facilities. Usually, one encounters in these reviews of thermal ecology discussions at various levels - individual organisms, groups or populations and ecosystems. These reviews can be grouped in several major categories: thermal tolerance, temperature and fish behavior, environmental impact of electric-power facilities, impingement, entrainment, and electric power facilities [SCOPE Report 2, 1972; Esch and McFarlane, 1976].

Information on ecological principles to be followed in economic development is also available, with special emphasis on ecosystems that are currently subject to heavy development pressure [Dasmann et al., 1973].

In another large category of general publications, authors deal with a specific measure of quality of aquatic environment and the effects of pollutants on that quality. Information on the broad topics of bacteriological, chemical and radioactive pollutants are available, as well as on the problems caused by pollution and specific methods of pollution control. In this category are classified publications dealing with biological indicators of environmental quality (the practical aspects of interpreting the biological manifestations of deteriorated environmental conditions), and with the quantitative techniques for the assessment of water body quality, especially of lakes [MacKenthum, 1973; Thomas et al., 1973; Reckhow, 1979; Cooper et al., 1976].

An important grouping of publications in this area are articles concerned with limnology and physico-chemical characteristics of specific water bodies in particular regions or countries of the world, such as Africa, India, New Zealand, Guatemala, etc., such as arid, semi-arid, temperate and tropical. Data are usually analyzed to provide descriptions of temperature, thermal stratification and location of thermocline, alkalinity, pH, turbidity, conductivity, dissolved oxygen, chlorides, nutrient conditions, algal species and numbers, distribution of flora and fauna, etc. Important general sources are Mishra and Yadav [1978]; Eccles [1974]; Brezonik and Fox [1974]; Forsyth and McColl [1974]; Rai [1974]; Driver and Peden [1977]; and Olsen and Sommerfeld [1977].

Hydrodynamics In this group are classified publications dealing with mixing and circulation of water and modeling of natural hydrosystems. Especially notable is the monograph by Fischer et al. [1979] which deals comprehensively with natural mixing phenomena from a hydromechanical viewpoint. A reservoir model, DYRESM, developed Imberger et al., [1977] is described in some detail. The approach used in this model, a conservation of total energy including wind shearing effects, may be useful for modeling of shallow ponds. The mechanisms of stratification in lakes are carefully analyzed by a number of researchers. Valuable sources include Jassby and Powell [1975]; Johnson and Merritt [1979]; Bedford and Babajimopoulos [1977]; Powell and Jassby [1974]; and Moretti and McLaughlin [1977]. The hydromechanical principles considered in these publications are generally useful for modeling of water bodies at all scales.

Temperature and Its Effects Temperature is probably the single most important physical characteristic of a water body in determining hydromechanical as well as water quality and ecological behavior. This parameter is the most often measured, and analyses of data are available in the literature for many different lakes and reservoirs.

The mechanics of heat exchange through the air-water interface is comprehensively treated by the TVA Engineering Laboratory, [1974]. Sometimes, general relationships between mean surface temperature and mean air temperature are utilized as predictive tools [Webb, 1974].

In many natural water bodies, an annual cycle of stratification occurs due to differences in temperature and changes in the heat budget. Many factors influence the shape of the vertical temperature profile including heat exchange by diffusion and processes within the water mass, heat exchange due to inflow and outflow of water in reservoirs, the temperature profile at the time of ice formation, etc. [Rahman, 1978]. Some publications deal generally with prediction of temperature on the basis of time-variable meteorological conditions and lake morphology [Stefan and Ford, 1975; Rahman and Marcotte, 1974]. Thermal stability and its effect on phytoplankton are also analyzed [Biswas, 1977]. A model which includes these effects has been developed by Chen and Orlob [1975] and tested on Lake Washington near Seattle.

Physico-Chemistry of Lakes and Reservoirs BOD and DO are the water quality parameters of lakes and reservoirs most often analyzed. These parameters have been modeled for lakes and values compared with observed values [Banks, 1976; Markovsky and Harleman, 1971; Chen and Orlob, 1975]. Field data indicate generally that oxygen demanding substances, both biotic and abiotic tend to be concentrated in the metalimnia of stratified lakes and reservoirs. The result is that high rates of oxygen depletion occur at these levels and below and that dissolved oxygen is often fully depleted [Gordon and Skelton, 1977]. Concentration of dissolved oxygen close to the bottom of such water bodies is often

very low, even zero. To alleviate adverse effects downstream, methods have been developed for increasing dissolved oxygen concentrations in the turbine releases from hydroelectric power plants. Systematic procedures have been used for evaluating promising solutions to low DO concentrations. One of the more popular methods is oxygen injection through small pore diffusers located upstream from the turbine intakes, [Ruane et al., 1977]. Laboratory tests were conducted on commercially available fine-pore diffusers to select those diffusers worthy of field testing. Laboratory tests included determination of bubble sizes and oxygen transfer efficiency. Field tests for oxygen transfer efficiency were performed for two different diffusers.

Total injection of air at the bottom of thermally stratified lakes and reservoirs might cause destratification, which can be quantitatively predicted by means of mathematical and physical models [Kranenburg, 1979]. The agreement between theory and model experiments is found to be satisfactory. Increasing the number of injection points was an effective means of speeding up the destratification process, but increasing the air flow rate was not. Another system of hypolimnetic aeration called side stream pumping, which uses liquid oxygen and a conventional water pump, was also tested. It was shown that hypolimnetic oxygen concentration increased from less than 0.5 mg/l to over 8.0 mg/l during 2 months of operation, while thermal stratification was maintained. These improvements created a suitable habitat for cold-water fish [Fast et al., 1975a and 1975b; Fast et al., 1977]. Another experimental program in turbine aspiration was conducted to develop techniques for improving the dissolved oxygen concentration of hydroelectric releases. The program, developed by Raney, [1977], involved water tunnel modeling of aspiration systems, in addition to prototype installations on existing hydroelectric facilities.

As noted, many methods for increasing dissolved oxygen concentrations of turbine releases have been suggested. In order to make the choice of one among them, an economic analysis was conducted. Fast et al., [1976] compared some of the methods on the economic basis and results are available.

Effects of aeration on water quality were examined also, particularly the effect of hypolimnetic aeration on nitrogen and phosphorus concentration [Garrels et al., 1977].

There have been a few attempts to relate some traditional trophic state indices, such as phosphorus concentration, chlorophyll-a concentration and transparency, to hypolimnetic dissolved oxygen, which is of direct relevance to existing water quality standards, particularly for fisheries management [Walker, 1979].

Data on limnological responses of impoundments to acid mine drainage are also available. Koryak et al., [1979] showed that in spite of only moderate vertical thermal gradients in the reservoirs, these inflows penetrate the impoundment as well-defined temperature-density currents. The depth of penetration and resulting mixing patterns depend on design and operation of the dam. The internal hydrodynamics of the reservoir, in turn, influences the chemistry and biology of both the impoundment and the outflow.

Nutrients There is such a wide variety of data on nutrients that it is difficult to classify them. Problems which are most often analyzed are related to potentially limiting nutrients, such as phosphorus, nitrogen, carbon, silicon, and trace metals. These problems include mechanisms of nutrient limitation of primary biological productivity, sources of nutrients and relative abundance, regeneration and reuse of nutrients in ecosystems [Middlebrooks et al., 1976; Fruh, 1974]. Some researchers involved in calculation of nutrient budgets have used the U.S. Geological Survey's flow-duration curve method developed for determining the long-term average sediment loads transported by streams. Rothandaraman and Evans, [1979] found that controlling phosphorus at the point sources is a major step in avoiding accelerated aging of the lake. Among the possible sources of nutrients are river and lake sediments. Decomposition of benthic deposits may have adverse effects on the quality of natural waters by exerting an oxygen demand and by releasing organics and nutrients into the overlying water. The oxygen uptake rate and the nutrient release rate from lake and river sediments were measured in long-term experiments and results are available [Fillos and Swanson, 1975]. On the basis of data, it can be concluded that the release of nutrients from natural sediments is controlled by physical-chemical reactions.

The sorption capacity for phosphorus of lake sediments depends on the oxygen concentration in the overlying water. Fillos and Biswas [1976] showed that in some lakes, when the phosphate concentration in the overlying water is high, above 1-2 mg/l, the sediments will sorb phosphorus from the overlying water under both aerobic and anaerobic conditions. Below this concentration, the sediments will release phosphorus under anaerobic conditions while they will sorb phosphorus under aerobic conditions.

There are data on vertical diffusion and nutrient transport for some tropical lakes. Roberts and Ward [1978] noted that during a period of 4.5 months when the water was stratified, nutrients were transported upward at a significant rate. The oxygen deficit rate can be correlated positively with phosphorus loading. Phosphorus budget studies have been conducted for Lake Michigan [Sager and Wiersma, 1975; Sridharan and Lee, 1974]. Results indicated the major sources of phosphorus, but it was concluded that the relative importance of the major sources varied considerably on a seasonal basis. It was possible to find an empirical method for estimating the retention of phosphorus in lakes on the basis of the relationship between phosphorus retention and several other lake and watershed parameters. Kirchner and Dillon [1975] reported that the predicted and measured values were in close agreement (r=0.94). A direct method of predicting summer levels of total phosphorus was suggested by Jones and Bachmann [1976]. A strong correlation was found between average July-August chlorophyll-a concentrations and total phosphorus concentrations [Charpa and Tarapchak, 1976].

A model based on conservation of mass was developed to simulate total phosphorus budgets for the Great Lakes [Chapra, 1977]. Phosphorus loadings were generated from variables indicative of human development, such as population and land use. Loadings are input to a budget model that can be solved for total phosphorus concentration as a function

of time. Projections indicated that if point source effluents were reduced to 1 mg/l of total phosphorus, all the lakes will show some improvement in trophic condition.

The potential trophic benefits to lakes of a 1 mg/l of total phosphorus effluent standard for municipal sewage treatment plants were examined by using two phosphorus mass balance models [Gakstatter, 1978]. The analysis included 255 lakes and reservoirs receiving municipal sewage treatment plant effluents and located in the eastern half of the United States. It was shown that 18-22% of the water bodies would benefit from a 1 mg/l effluent standard. If the requirement was zero phosphorus, 78% of the water bodies would benefit.

Some studies of seasonal and spatial distribution of nutrients have been conducted by Stewart and Markello [1974] and Gruendling and Malanchuk [1974]. Results of measurements indicated that variations may reflect the geochemistry of the area, local differences in lake hydrology and mixing characteristics, and the supply of nutrients from soil, man and precipitation. Specific values for nutrient loading derived from these calculations do indicate the relative importance of human contributions and provide an aid in management considerations.

Ecological Interaction All publications dealing with different ecosystems and interaction between limnological characteristics of lakes and reservoirs and flora and fauna are classified in this group.

In eutrophic lakes, the supply of light and the extent of turbulent mixing near the water surface often control the actual occurrence and disappearance of algal blooms [Stefan et al.,1976]. While nutrients provide necessary material for a high growth potential, light and mixing provide energetic controls. It is possible to find an expression for an equilibrium phytoplankton concentration under given physical conditions. Also, effects of temperature on growth constants of some particular alga are examined, as well as response of lake algae to addition of nutrients, such as phosphate, nitrate and silica and to iron ore processing wastes. Based on changes in the rate of carbon fixation, phosphate stimulated approximately 80 percent of the cultures to which it was added, and nitrate and silica were nonstimulating. Iron ore processing wastes were found to be neither toxic nor stimulating [Plumb and Lee, 1975].

Changes in temperature, nutrients, etc. can cause ecologic changes, so monitoring of the environment may be very useful. Van Belle and Fisher [1977] noted that the data are assumed to consist of a species-frequency list collected at several sites, in order to enable statistical analysis. The major statistical problem with analyzing such lists is the establishment of an appropriate frequency distribution under some suitable hypothesis. After assuming an appropriate frequency distribution, statistical tests can be applied to determine whether biological communities or changes in biological communities are connected with ecological changes some distance apart from these communities. Information on the rationale behind the use of biological variables in environmental monitoring of lakes is provided, as well as the principles of variable selection and the limitations of data usability in Widerholm [1980]. Difficulties might arise in the use of saprobic or indicator organism systems in developing water quality criteria when organisms are not known at the species level. Generic identifications are generally useless, because particular species may vary widely in ecological tolerance [Resh and Unzicker, 1975]. Some authors suggest cyanophage analysis as a biological pollution indicator. The detection and control of enteric viruses in wastewater is a primary health concern. Present wastewater standards do not involve practical assays for, or require virus removal from, discharged effluents. Cyanophages are nonpathogenic and present throughout the year in wastewater. A proposed cyanophage detection procedure is a practical and inexpensive animal virus indicator and could serve as a replacement for the coliform test. A description of the procedure is available [Smedberg and Cannon, 1976].

Hydraulics and Hydromechanics of Ponds, Small Lakes and Reservoirs

Hydrodynamics and the Effects of Geometry and Hydrology All publications dealing with fluid movements in ponds, small lakes and small reservoirs are classified in this group. Circulation induced in a water body results primarily from wind stresses and horizontal temperature gradients. A three-dimensional model was developed by Uzzel and Ozisik, [1977] for the prediction of steady-state circulation induced in the far field regions of shallow lakes. For the case of lakes with rectangular geometry and uniform depth, explicit analytical solutions for the velocity distribution are available. The result of the analysis shows that a negative temperature gradient along the lake in a given direction gives rise to a flow in the same direction at the upper layer of the lake and to a reverse flow at the lower layer. Circulations induced by horizontal temperature gradients may be as important as those generated by wind stresses.

The shear stress due to wind action on a shallow lake or lagoon creates a velocity distribution in the vertical direction. Some information is available on the relationships between vertical turbulent diffusion, surface reaeration and wind velocity, depending on the wind shear stress coefficient [Banks, 1975]. It is noted that publications on this topic are comparatively few in number.

The effects of both the inflow and outflow on the dynamics of a reservoir are described and a new Lagrangian one-dimensional model is proposed by Imberger et al., [1978] for deep hypolimnetic mixing. The model contains only four universal constants. Data from one complete annual cycle of the salinity and temperature distribution from a Western Australian reservoir are used to calibrate the model. A complete discussion of this model, DYRESM, appears in Fischer, et al. [1979].

Effect of Hydraulic Structures This group of publications concerns defining what types of structures should be selected for study in view of the potential effect on the environment, and identifying how hydraulic structures are interrelated with their environment. Information on categories of hydraulic structures and their specific environmental effects are available. An example developed by King [1978] examines the effects of impoundments on downstream water quality.

The major hydraulic structures affecting the environment are hydroelectric power plants. They change the natural conditions of these water bodies through both short-term and long-term impacts. Therefore, changes in water quality, rates of erosion, fluctuations in water temperature and water flow, and eutrophication must be studied in planning future hydroelectric installations. Descriptions of reported physical, chemical and hydrodynamic changes associated with dams are available, as well as relationships of these changes to fish and benthic communities. El-Shamy [1977] briefly considered several aspects of the impacts of the hydroelectric projects and changes in the lower Susquehanna River. The sites of four large dams were evaluated in light of disruption of the upstream runs of the previously existing migratory fishes. Changes in the structure of the benthic community were also analyzed.

Dams and impoundments may affect the migration of fish. This problem is recognized and data on migrations of juvenile chinook salmon and steelhead from tributaries of the Snake River as far downstream as The Dalles Dam on the Columbia River are available [Raymond, 1979]. New dams constructed on the Snake River adversely affected survival and delayed migrations of juveniles. Significant losses of juveniles in 1972 and 1973 were directly responsible for record-low returns of adults to the Snake River in 1974 and 1975. Major causes of mortality were passage through turbines at dams, predation, delays in migration through reservoirs in low-flow years and prolonged exposure to lethal concentrations of dissolved gases caused by spilling at dams during high-flow years. It was found that mortality of chinook salmon and steelhead resulting from new dams differed with respect to area and cause. In order to avoid mortality, different fish handling facilities were analyzed, such as angled screens and louvers [Taft and Mussalli, 1978]. They may be used for diverting fish at power plants. Louvers have been shown to be greater than 90% effective in diverting a variety of fish species in both laboratory and prototype studies. Studies with angled traveling screens, conducted in 1978, showed that they are 100% effective in guiding fish to bypasses. The inherent difficulties of screens, i.e., the necessity of lowering the approach velocity, poor velocity distribution across the screen, and danger to fish, may be overcome by the installation of a perforated-pipe inlet with an added internal perforated sleeve, as concluded by Richards and Hroncich [1976]. The benefits of such a device, i.e., relative ease of maintenance, uniform approach velocity, uniform inflow and protection for fish, are greater than when ordinary physical screening is used.

Generally, the information available on hydromechanical behavior of small water bodies is sparse. Few models exist which are addressed specifically to questions of concern in hydrodynamic modeling of aquaculture ponds.

Water Quality of Small Lakes, Ponds and Reservoirs and Effects on Fish

Temperature In a study of pond temperatures in temperate and tropical climates, seasonal changes played major roles [Young, 1975]. Four different periods were recognized: periods of low, rising, high and declining temperature. In the course of a year, the range between the lowest and highest average temperatures was greater in the temperate pond. The spans between the average minimum and the average maximum weekly water temperatures in the warmest months of the year in the tropical pond were greater than those found at any time of the year in the temperate pond. The average weekly air and water temperatures showed the same pattern of seasonal fluctuations. In the tropical pond, the average weekly air temperatures were always less than the average minimum weekly water temperatures, where in the temperate pond they were below, within or above the spans between the average minimum and average maximum weekly aquatic temperatures, according to the time of year. In both ponds, diurnal fluctuations were absent during the cooler months; the amplitudes of the fluctuations in the warmer months varied according to the time of year, and were greater during the warmest months in the tropical pond. In both ponds, lowest temperatures were recorded sometime between 02:00 and 10:00 and highest between 12:00 and 20:00 hours. The influence of temperature on the life-cycle of fish was acknowledged and discussed.

In an assessment of the effects of stratification on the depth distribution of gizzard shad, white crappie, freshwater drum and black bullhead [Gebhart and Summerfelt, 1976] it was noted that they were markedly affected by conditions of stratification. During the period of greatest stratification, the distribution of all species except the bullhead was limited largely to oxygenated water above the hypolimnion. Fish depth distribution increased significantly after the fall overturn. Also, it was observed that the diet of channel catfish varied considerably with water temperature [McNeely and Pearson, 1977].

DO, BOD and Eutrophication Effects on Fish Effects of low dissolved oxygen concentration on channel catfish were analyzed by Tucker et al., [1979] and results are available. Test fish were stocked in 0.02 and 0.04 hectare ponds without aeration at three rates (4,962, 10,007, and 20,385 fish per hectare) and fed daily. Each treatment was replicated six times. Maximum feeding rates of 34, 56 and 78 kg/ha, respectively, were reached by midsummer. At the lowest level of treatment, no dissolved oxygen (DO) problems occurred and survival was 99%. At the medium treatment level, the lowest recorded DO concentration frequently was below 2.0 mg/l and some fish suffocated during an oxygen depletion in one pond, but survival still averaged 93%. For the high level treatment, DO at dawn was usually below 2.0 mg/l in August and September. Fish mortalities resulted from DO depletion in three ponds at the high level of treatment, but survival averaged 83%. Nitrate-nitrogen and un-ionized ammonia never reached concentrations recognized to be lethal to channel catfish in any of the treatments. However, concentrations of un-ionized ammonia were possibly high enough to have adversely affected growth. Even though the average weight of individual fish decreased, harvest weight of fish increased from low to high treatment. An economic analysis was also conducted and results are available.

Consumption of oxygen by planktonic communities of pond waters may be predicted from chemical oxygen demand (COD) and temperature [Boyd et al., 1978]. Correlation was found to be good (r^2 = 0.85) in ponds where planktonic organisms are the major source of turbidity. Secchi disk visibility

may also be used to estimate COD (r^2=0.81) or consumption of O_2 by planktonic communities (r^2=0.82). In order to calculate nighttime declination in dissolved oxygen for channel catfish ponds, a computer simulation model was developed. This model incorporated data on plankton respiration from the study of the same authors and data from the literature on respiration by fish, respiration by organisms in the mud and O_2 diffusion. The validity of the model was tested for two catfish ponds. Measured and calculated DO concentrations usually agreed within ±10%. Secchi disk visibility and COD values may be used in the computer simulation to estimate O_2 consumption by plankton, depending on conditions in a particular pond. A series of tables was prepared which give the minimum acceptable Secchi disk visibility and the maximum permissible COD which may be tolerated in a particular pond without danger of DO depletion during the night. These tables will be useful to fish pond managers. A simple graphical technique for estimating DO concentrations is also suggested.

The daytime increase in dissolved oxygen concentration of pond water may be estimated from solar radiation, chlorophyll-a concentration and percentage O_2 saturation at dawn, or from solar radiation, Secchi disk visibility and percentage O_2 saturation at dawn [Romaire and Boyd, 1979]. A computer simulation model for predicting the effects of cloudy weather (low solar radiation) on DO depletion was developed for channel catfish ponds. The model combines daytime DO increase estimated on the basis of solar radiation data and Secchi disk visibility data and the nighttime decline in DO due to respiration by the plankton, fish and benthic communities. Results from the study demonstrated that the combination of dense plankton blooms and low levels of light intensity were closely related to low concentrations of DO.

Negative effects of low dissolved oxygen concentration can be avoided by aeration, as concluded by Hollerman and Boyd [1980]. Channel catfish were stocked in 0.02 and 0.04 hectare ponds at 20,385 fish per hectare and fed daily. Six ponds were aerated nightly (2 to 6 hours) and six ponds were not. In aerated ponds, no dissoved oxygen problems occurred and survival was 92%. In all unaerated ponds, DO depletion was observed and fish mortalities resulted; survival was 40%. Nitrite-nitrogen concentrations were significantly higher in the aerated ponds, but never at levels reported as lethal to channel catfish. Concentrations of un-ionized ammonia were high enough in both aerated and unaerated ponds to adversely affect growth. Results of an economic study are also available.

In order to examine the effectiveness of different techniques of emergency aeration, dissolved oxygen concentrations were depressed in 0.57 hectare fish ponds through algicide treatment [Boyd and Tucker, 1979]. The most effective device for emergency aeration was a paddlewheel aerator powered by a tractor. Different types of pumps were tested and results are presented. Their efficiencies were shown to be lower than that of the paddlewheel aerator.

Another procedure for raising dissolved oxygen concentration is to reduce phytoplankton density [Tucker and Boyd, 1977]. Treatment of channel catfish production ponds with biweekly applications of 0.84 kg/hectare copper sulfate was ineffective, but three periodic applications of simazine totaling 1.3 mg/l drastically reduced phytoplankton density. However, extended periods of low dissolved oxygen concentrations following simazine applications resulted in decreased fish yields and poor conversion ratios as compared with control ponds.

The catfish processing industry as a whole has been examined for its pollution potential. A single modern plant was studied by Mulkey and Sargent, [1974] to determine the waste characteristics of in-plant and total effluent streams. It was found that volume and concentration of the wastewater may be reduced by more effective solids removal and recycling of process waters. Process changes and water flow modifications were also proposed.

Physico-chemistry Data on seasonal and diurnal fluctuations of the physico-chemical conditions in temporary ponds are available. Physico-chemical parameters studied were pond volume, air, water and substratum temperature, pH, conductivity, and dissolved oxygen concentrations [Khalaf and MacDonald, 1975]. A study of unfertilized ponds in pastures and woodlands was also conducted. It was shown that unfertilized ponds in pastures are more eutrophic than unfertilized ponds in wooded locations. It was suggested that fertilizer application rates currently used in bass-sunfish ponds in some regions of the USA may be greatly reduced in many pasture ponds [Boyd, 1976b].

The effect of draining was also analyzed [Boyd, 1976a]. Percentages of small particles and organic matter in pond muds increased along transects from shallow to deep water in four fish ponds which had never been drained. Gradients in texture and organic matter were similar to those reported by nearby ponds which had been drained periodically.

Toxics and Heavy Metals Combined effects of chemicals and various temperatures on aquatic organisms were studied by Cairns et al., [1975]. The frequent association of power plant and other heated wastewater discharges with potentially toxic chemicals justifies an evaluation of these combined stresses on aquatic organisms. Substances such as ammonia, cyanide, trace metals, pesticides and herbicides, phenolics, and chlorine exert their toxic effects through a wide variety of mechanisms which, in turn, are influenced by temperature. Also of considerable interest are the effects of interactions between temperature and substances such as antibiotics, on microorganisms. Information on these effects, available in the literature, may assist management personnel in setting standards and providing the background for designing new studies.

A critical evaluation of material and methods to be used for the study of behavioral responses of fish to polluted water [Larrick et al., 1978]. In this connection, the feasibility of using aberrations in fish movement patterns in response to intoxication (measured by infrared light beam interruption) to monitor and detect pollution was investigated. Acute and sublethal toxic effects were deleted for copper, cadmium, cyanide, mercury, phenol, and ammonia. The system proved satisfactory for detecting phenols and ammonia, much better than previous monitoring systems based on fish respiratory responses to intoxication, but was less effective for the other toxicants investigated [Morgan, 1979].

Effects of different toxic materials on aquatic organisms were examined by Katz [1977]. In his study, 23 nitrogenous compounds were selected for the determination of chlorine dissipation in relation to toxicity prior to and after the addition of fish. These toxicities, which were much less than that of free chlorine, varied directly with the logarithm of fish mortality and the rate of chlorine dissipation in the presence of fish. Thus, it was concluded that nitrogenous compounds alter the toxicity of total residual chlorine.

The use of chlorine by the power industry for slime control in freshwater systems generally differs from the use of chlorine for wastewater disinfection, since it is used intermittently rather than continuously. A typical power plant will chlorinate three times a day with 0.5 to 0.75 mg/l of chlorine with a 15 to 30 minute deviation at each chlorination period. Although extensive research programs have been conducted evaluating the toxicity of continuous exposure to chlorine, limited literature is available to evaluate the toxicity of intermittent exposures to chlorine. A laboratory study designed to identify the relationship between frequency of exposure, concentration, duration of exposure, and the expression of lethality in fish, showed that total time of exposure was the most important parameter in predicting lethality [Dickson et al., 1977; Mattice and Zittel, 1976].

Intermittent chlorination has different effects on different fish species. Data from laboratory studies of the behavior of different species of fish, exposed to either free chlorine or monochloramine, are available [Heath, 1976]. It was shown that temperature has relatively little effect on the toxicity of intermittent chlorine to the species tested. Also, it was shown that free chlorine was significantly more toxic than monochloramine and it was suggested that water quality criteria for the protection of fish should, in the future, take this differential toxicity into consideration.

Some species may acclimate to chlorine. Acclimatization of fathead minnows and lake trout to residual chlorine and bromine chloride was studied by DeGraeve and Ward [1977]. Chronic effects of nickel and hydrogen cyanide on the fathead minnows were examined, also. Nickel (as the chloride salt) at concentrations ranging from 1.6 to 0.08 mg/l in a continuous-flow chronic bioassay had no effect on survival or growth of first-generation fathead minnows [Pickering, 1974]. However, the number of eggs per spawning and the hatchability of these eggs were affected. Methods for estimating toxicity of nickel for other species of fish are suggested. Egg production rate was most sensitive when hydrogen cyanide was applied. The highest level of toxicant with no adverse effect was between 12.9 and 19.6 mg/l of hydrogen cyanide [Lind et al., 1977].

Fish eggs and larvae may suffer from dissolved ozone. To find concentrations of disolved residual ozone lethal to fish eggs and larvae during brief exposures, Asbury and Coler [1980] performed continuous-flow toxicity tests with eggs of yellow perch and fathead minnows, eggs of white suckers, and larvae of bluegill sunfish. The 50% and 99% lethal concentrations with confidence limits were calculated. Eggs of the species tested were more tolerant than larvae. It was concluded that because of the sensitivity of the larvae, residual ozone concentrations in natural waters should remain well below 50 mg/l (or micrograms per liter).

Examinations of the uptake rates by some fish species of methylmercury, biosynthesized in sediments, were conducted by Shin and Krenkel, [1976] to find the effects of various environmental conditions, such as temperature, degree of organic pollution, chloride ion concentration and degree of mercury pollution. An attempt was made to quantify the effects on the overall methylation activities of microorganisms of varying environmental parameters such as temperature, BOD, Cl^-, degree of mercury pollution and pH. A rate equation and reaction order were introduced. It was found that for the conditions examined, the methylation reaction was first order with respect to the molar concentration of mercury. Rate constants of the methylation reactions of mercury and the half-lives of mercury contained in the sediments under given conditions were determined.

The locomotor response of goldfish to a steep gradient of copper ions was examined in Westlake et al., [1974].

Ecological Interactions Some general publications dealing with small lakes, reservoirs and ponds exist for different regions of the world. These publications discuss some aspects of inland fisheries, such as biological monitoring with respect to detecting changes in the aquatic biota, its use as a basis for the classification of waters and also as a guide to potential fish production [Beadle, 1974; Salanci and Ponyi, 1975; Alabaster, 1977; Lowe-McConnell, 1975].

Primary production of fish ponds was analyzed by Jana [1979]. Estimates of primary production in relation to bacterioplankton growth kinetics were made for three fish ponds with mono and polyculture in the same region of the USSR. Because the basic process of primary production is dependent on conditions such as temperature, light and nutrient rather than on fish species, almost similar production rates were obtained in all three ponds. A maximal gross production, coupled with bacterioplankton peak was recorded in July with the rise of temperature of the water, while minimal production was recorded in September.

It has been noted by Boyd et al. [1977] that during windy weather in March and early April, dense populations of the blue-green alga frequently develop in fish ponds in Alabama. Massive die-offs of this alga occur during prolonged periods of calm, clear, warm weather between mid-April and mid-May. Dissolved oxygen concentrations decline following die-offs and fish kills may result.

Data on different ecosystems, such as pond ecosystems in India, prairie lakes in Nebraska, a salmon lake on Kamchatka Peninsula, a pond in Canada and a pond in the U.K. are available [Munawar, 1974a, Munawar, 1974b, Munawar, 1975; Sreenivasan, 1974; Schwartzkopf and Hergenrader, 1977; Sorokin and Paveljeva, 1978; Kwei, 1976; DSO and Foster, 1974]. Parameters usually involved are alkalinity hardness, electrical conductivity, pH, Secchi disk turbidity, temperature, and chlorophyll-a concentrations. Descriptions are provided to indicate how these parameters affect primary production of the ecosystem, vertical distribution of fish species, phytoplankton, standing crops, etc. Effects of rainfall,

evaporation, tides, solar radiation, etc., are also examined.

An important effect on ecosystems is the activity of man. One of the major disturbances of aquatic ecosystems is caused by merely damming a river. The relative compositions of the major fish families in Lake Kainji in Nigeria between 1974 and 1975 were analyzed by Blake [1976] and Lewis [1974] and compared with pre- and post-impoundment of Niger River data. The dominant commercially valuable fish was changed and data on other related changes are also available. A similar process is recorded after damming the Volta River in Africa by Petr [1974].

Another major activity of man affecting ecosystems is the discharge of thermal effluents. Data on this effect on Lake Wabamun, Alberta, Canada, are reported by Hickman [1974].

Also, artificial destratification of lakes may affect ecosystems [Wilhm and McClintock, 1978]. Changes in species composition and diversity of benthic macro-invertebrates during summer and fall were compared in an area of an artificially destratified lake and in an area which was not destratified. Numbers of species, diversity, and density were significantly correlated with the concentration of dissolved oxygen, while none of the biotic variables were correlated with temperature.

Comment A substantial body of literature on water quality in lakes and reservoirs exist but little deals directly with the problems of very small water bodies such as ponds. Basic water quality-ecological interactions in such systems are fairly well known and appear to be transferable to aquaculture ponds for the purpose of model development.

Models of Aquatic Systems

One-Dimensional Temperature Models Simulation of temperature variations in deep, thermally stratified reservoirs or lakes has been successfully accomplished by application of the one-dimensional advection-diffusion equation and the heat energy conservation equation. Two mathematical models of very similar structure, one developed by Water Resources Engineers, Inc. [WRE, 1968] and the other by the Parsons Laboratory at MIT [Huber, et al.,1972] are most widely used today. Both have utilized the heat energy budget calculation procedures developed by the Engineering Laboratory of TVA [1974]. Solution techniques for the models are different--one is explicit, the other implicit--but the results are comparable, generally in good agreement with prototype observations. Both models are well documented.

Swenson [1978] suggested a numerical procedure for the prediction of the thermal structure of the ocean and lakes. The mathematical formulation of this problem is based on the heat energy equation in its one-dimensional form. A turbulence model provides a means of calculating the turbulent transport coefficient for heat. Two momentum equations for the mean flow are also solved, since the turbulence model requires information about velocity gradients. Through the process of verification, it is shown that the thermal structure of lakes is predicted very accurately. This is demonstrated by a comparison of measured and predicted seasonal thermal structure of Lake Velen in Sweden.

One-Dimensional Water Quality Models Modeling of other water quality characteristics of reservoirs, a logical extension of thermal modeling, was carried out by both the WRE and MIT groups in the early 70's. A water quality-ecologic model of stratified impoundments was proposed originally by Chen in 1968 and led to the development under OWRR and EPA sponsorship of the model LAKECO [Chen and Orlob, 1975]. This model, which includes some 22 different state variables, both biotic and abiotic, has been applied successfully by the developers and government agencies in simulations of water quality changes in Lake Washington and a variety of artificial impoundments.

The MIT group extended their temperature model to include simulation of DO and BOD and demonstrated its application on Fontana Reservoir in the TVA system [Markofsky and Harleman, 1973]. An improvement in the solution technique for one-dimensional water quality models for impoundments was the introduction by Baca and Arnett [1976] of the finite element method. The resulting model, which has most of the capabilities of LAKECO, avoids problems of numerical mixing, instability, and adapting to steep gradients.

A recent development which is uniquely different than previous modeling approaches is the Lagrangian slab model of Imberger, et al. [1977]. Based on budgeting turbulent kinetic energy in horizontal slabs of varying thickness, the model is capable of simulating simultaneously both temperature and salinity distributions in small to medium sized reservoirs. The model utilizes only four "universal" constants that can be evaluated from field performance.

Two-Dimensional Circulation Models Excellent reviews of modeling wind-driven circulation in lakes are provided by Simons [1973] and Cheng, et al. [1976]. These show that a well-developed capability exists for modeling two-dimensional, vertically mixed impoundments. It is represented in the simplest form by so-called single layer, storm surge models such as have been applied to the Great Lakes [Platzman, 1963] and to shallow coastal seas [Hansen, 1962] [Reid and Bodine, 1968]. Models of this type are capable of providing approximate descriptions of circulations induced by winds and pressure differences associated with major storm events.

Improved descriptions of circulation in shallow systems are available through application of models for vertically mixed estuaries, like those of Leendertse [1967], Masch [1969], Waldrop and Farmer [1973] and Codell [1973]. Based on the phenomenological equations of motion in two-dimensions, such models are capable of providing good representation of current velocities and water surface elevations under highly unsteady conditions related to wind, tide, or hydrologic fluxes. The models are orthogonal, using central finite differencing, usually of an alternating direction or leapfrog type. Both implicit and explicit schemes are employed. Models of this type are well documented and widely applied.

An attractive alternative for two-dimensional, vertically-mixed systems is a finite element model developed by King and Norton [1973]. The model utilizes elements of triangular, rectangular, or curved configuration and of variable size to represent irregular boundaries and topographic features of the prototype. Liggett [1969], Gallagher [1975], and Cheng, et al. [1976] have demonstrated the potential of the method for shallow lake systems.

Multilayer Impoundment Models Density stratification induced by temperature, salinity, or suspended solids required more rigorous mathematical representation of the hydromechanics of impoundments. The multi-layer lake models of Simons [1973], referred to by Cheng, et al. [1975] as Type I, are most representative. They have been applied with reasonable success to several of the Great Lakes and to Lake Vanern in Sweden [Simons, et al., 1977]. In the latter application it was recognized that model performance was most sensitive to empirically determined coefficients, e.g., eddy diffusivities, and that reduction in model detail and conceptual elegance may be justified as a trade-off against costs of computation.

Two-dimensional stratified flow models designed to simulate the hydrodynamic behavior of long, narrow impoundments are represented by the finite element model, RMA2, developed by King and Norton [1975] and by a finite difference model under development by Edinger and Buchak [1975]. Such models have been tested primarily against laboratory experiments and, in the case of RMA2, adapted for simulation of estuarial systems. The lack of prototype data has prevented direct verification of model capability.

Two- and Three-Dimensional Water Quality-Ecologic Models A broad range of publications deal with modeling of aquatic ecosystems, both in theory and with applications. It is possible to find descriptions of the application of mathematical modeling techniques to practical problems of water quality management of lakes, rivers, and estuaries. Pertinent questions concerning the environmental impact and control of effluents are explored through presentation of examples where models have been used. Some studies contain results or ideas not currently being applied by practitioners, but which have potential--and which may be part of the next generation of models [Canale, 1976]. Publications dealing with how biological concepts can be formulated in mathematical terms and how the resulting formulations are used in research of ecosystems are available, also [Gold, 1977]. Problems considered in these works are: the basic concepts of system states, variables and parameters, system decomposition, graphical representation of relations between variables, input-output relations, scale dimensions and similarity as related to biological systems, the concept of probability, the translation of a conceptual model and the relationship of the model to the real world system.

The vertical one-dimensional assumption of the earlier lake and reservoirs models was examined with respect to its validity for mathematical ecological models [Ford and Thornton, 1979]. An analysis of time and length scales characterizing the hydrodynamics, chemistry and biology shows that the two scales are necessarily coupled and that their interaction dictates both upper and lower bounds for the lake size that can be described by a one-dimensional model. According to Niemeyer [1978], an efficient procedure for solving an arbitrary number of coupled vertically integrated transport equations can be achieved by using some features of both finite difference and finite element methods.

Modeling of the transport and dispersion of conservative substances in shallow lakes is represented in a model by Lam and Simons [1976] that has been demonstrated on Lake Erie. Non-conservative substances, including phytoplankton and nutrients, have been treated in a model of Green Bay by Patterson, et al. [1975] and a phytoplankton productivity model of Western Lake Erie by DiToro, et al. [1975]. In each of these examples the models are driven by a flow field derived either from field observation or a companion circulation model. The Lam and Simons model treated the lake system as either vertically mixed (1 layer) or stratified (2 layers) while the other models assumed vertical homogeneity.

The phenomena of eutrophication have been modeled by the gross nutrient budget approach advanced first by Vollenweider [1969] and later extended by Snodgrass and O'Melia [1975], Larsen and Mercier [1975] and Bella et al. [1976]. More complete representations of the two and three dimensional and temporal variations of nutrient-biota interactions in lake systems are exemplified by the models of Thomann, et al. [1975] and Chen et al. [1975] of Lake Ontario.

Three different models were envisioned by Thomann, ranging from a simple three layer (epilimnion, hypolimnion, benthos) model to one with 7 layers and 67 segments and up to 15 variables. Only LAKE 1, the three-layer model, was verified against prototype measurements.

The Chen Lake Ontario model considered some 15 different classes of biotic and abiotic substances, and considerably expanded biological compartmentalization from that of his earlier model, LAKECO. The lake was represented by 41 surface elements and 7 layers, a total of 109 discrete physical units. The model was tested to demonstrate functional capability but was not verified.

CLEANER, a comprehensive lake ecologic model with 34 state variables, is a product of the International Biological Program by researchers at Renssalaer Polytechnic Institute [Park, et al., 1976]. It conceptualizes the "lake" as a 1 meter-square column which may be divided into as many as 10 cells to provide vertical resolution. The model is capable of simulating, for both the epilimnion and hypolimnion, three types of each of the following groups: phytoplankton, zooplankton and fish. Also, it is possible for each layer to simulate dissolved inorganic nitrogen, phosphate, dissolved and suspended organic matter, dissolved oxygen and decomposers. The model has been applied to a variety of prototype situations including Lakes George and Sarasota in New York and several lakes in Europe, and it has been found that it gives simulations which are reasonable when compared with available data. Later, the model CLEANER was generalized by Youngberg [1977] so that it could be applied to reservoirs, well stratified lakes, shallow lakes, and high mountain lakes. Potentially, the model may be applied in studying problems of eutrophication, fisheries management and

thermal pollution. CLEANER was evaluated and adapted in cooperation with scientists in several leading European hydrobiological laboratories, and it has proved to be useful in representing highly diverse limnological conditions Submodels are included for rotifers, benthic algae, stratification, wave agitation, reservoir interflow and throughflow. A procedure for sensitivity analysis was developed. The results were helpful in evaluating the model and in setting error ranges on the simulations. They also can be used to indicate the precision required in measuring input data.

On the other hand, some limitations of models must be moted. Some of the problems encountered in the design of a predictive water quality model for a large lake are discussed with reference to Lake Ontario and within the framework of a simple dynamic phosphorus model which incorporates the essential mechanisms of complex plankton models. By fitting the model to a seasonal data base, Simons and Lam [1980] and Babajimopoulos and Bedford [1980] have shown that equally satisfactory simulations are obtained with a different value of parameters and regardless of conditions of annual periodicity imposed on the solution. By comparison of model output with long-term observations, it is demonstrated that seasonal verification studies of dynamic models by themselves are not sufficient to confirm the utility of such models for predicting long-term trends.

The state-of-the-art of water quality-ecological modeling is probably fairly well represented by the phytoplankton productivity models of DiToro, et al. [1975] and Thomann, et al. [1975], the water quality-ecologic models of Chen [1970] [Chen and Orlob, 1975] and Chen, et al. [1975]. CLEANER, the BPI-RPI model [Park, et al., [1976] adds rigor to biological characterization of impoundments. It appears that model sophistication has gone somewhat beyond understanding of prototype behavior.

Algae-Nutrient Cycles It is concluded by Tapp [1978] that eutrophication analysis can be performed with both simple and complex models. The condition of the reservoir was examined for both types and, for case of 90% and 99% point source removal. Light and temperature are probably the most important parameters determining the process of eutrophication.

Formulations have been developed to model the adaptation of phytoplankton to changing conditions of light and temperature. The photosynthetic response to the interaction between these two parameters is also represented in the work of Groden [1977]. Adaptive constructs have been made in the ecosystem model CLEANER with the result that they increase the long-term applicability of that model under changing conditions, as well as the possibility of applying it to sites with differing conditions. A submodel for internal nutrients, critical to prediction of phytoplankton growth dynamics, has been developed by Desormeau [1978]. Constructs were designed to represent storage of nutrients by separate mechanisms for nutrient uptake and assimilation, multiple nutrient limitation by threshold hypothesis, and light dependent photorespiration. The model was calibrated and validated on the basis of data for lakes in Norway and Austria.

The use of the catastrophe theory to obtain a predictive model of eutrophication phenomena is examined and applied to the case of small, highly eutrophic ponds by Duckstein et al., [1979]. Phytoplankton dynamics were represented by a non-linear differential equation derived on the basis of phenomenological considerations. This equation can be reduced analytically to the reasonable form for a cusp catastrophe model. Numerical solution of the dynamic equation is calibrated on the basis of data taken during a phytoplankton bloom in small ponds recorded earlier. Implications for fish ponds are given and possible use of the catastrophe theory approach to model algal succession is discussed.

Some models usable for predicting the effects of changes in environmental factors, such as nutrient inputs in aquatic ecosystems, have also been developed [Slawson and Everet, 1976]. A methodology for distributing primary productivity measurements among segments of the algal population has been formulated and tested. Such segmentation is necessary to develop a biological population model that allows consideration of biotic diversity, food web stability and ecosystem complexity. Total algal productivity rates were adequately approximated as the sum of the activity of each algal division.

Some very specific models are also available. A three-compartment mathematical model was developed by Greeney et al. [1974] to represent a phytoplankton population having the capacity for intracellular storage of nitrogen in a nitrate-limited environment. Model coefficients were estimated from data reported in the literature. By incorporating intracellular storage in the model, an organism's ability to compete at any given time was based not only on current environmental conditions, but also on the past history of nutrient uptake. The model was used to demonstrate the effect of environmental fluctuations on the competitive ability of two phytoplankton populations.

A mathematical model was developed to simulate the impact of storm loads on phosphorus, fecal coliform and dissolved oxygen concentrations in eutrophic lakes and determine the need for storm overflows [Freedman, et al., 1980]. Results obtained by the model showed that combined sewer and storm loads have a significant impact on lake fecal coliform, but little effect on phosphorus and dissolved oxygen concentrations. Observed variations in dissolved oxygen concentrations of the lake under consideration were caused by changes in chlorophyll-a, light and wind. As a consequence of the modeling analysis, a limited control program for combined sewer overflows was designed, which included only disinfection and removal of objectional solids. Reductions in storm loads of nutrients and BOD would not provide any significant improvements in water quality of analyzed lakes and were not recommended.

A model for evaluating the fate of toxic substances in fish was developed by Leung [1978]. Values of important parameters are included and simulated values for methoxychlor and DDT are compared to available data.

Some models have been formulated to simulate fish biomass dynamics, as well as interacting fish species on the basis of food competition [Hackney and Minns, 1974; Kitchell et al., 1974; Thornton and Lessem, 1978].

Aquaculture Practice, Economic Models and Management A very limited number of papers are available that deal with modeling for optimum and maximum yield, the implications of these concepts for commercial and recreational fisheries and their national and international applications. Few, if any, appear of much value for pond aquaculture.

Most hatchery management decision problems are multilevel and very complex, involve interactions between different areas of analysis and are often incorrectly defined [Tomlinson and Brown, 1979]. Techniques of analysis most commonly applied, such as operations research, cost benefit analysis, econometrics and Bayesian analysis are valuable, but limited. In complex decision problems, decision makers often try to minimize potential regrets and maximize utilities along certain limited and separable measures of benefits at the expense of overall optimality.

Regression analyses have been used for over twenty years to develop useful statistical relationships between estimates of fish catch and various members of a set of abiotic and biotic variables. Empirical predictions of fish yield, based on regression analyses, exist for large North American lakes [Matuszek, 1978]. Economic models of fisheries are available for a number of different regions of the world: the Gulf of Mexico (Galveston Bay, Texas), Zambia, Canada, and some tropical lakes in Africa and India [Sheenan and Russell, 1978; Melack, 1976; Toews and Griffith, 1979; Grant and Griffin, 1979]. What all of these models have in common is their empirical structure. Usually, they are based on regression analysis with some additional parameters such as primary productivity, standing crop or gross photosynthesis. Their use in pond aquaculture appears limited.

Special Models A number of useful special models of impoundments were encountered. These included models for routing runoff through the Great Lakes, simulating conservative water quality in reservoir systems, estimating sediment accumulation in reservoirs, evaluating candidate reservoir systems, calculating bank storage adjacent to reservoirs, and predicting the effects of landslides into reservoirs. None of these were considered of much value in the present research.

Comment The ecologic models that have been applied to lakes and stratified reservoirs, like LAKECO, CLEANER, MS. CLEANER, etc., have been constructed for the most part following the classical Latka-Volterra equations, with mass and energy conservation principles observed. Adequate hydromechanical descriptions are usually assumed rather than simulated. Nevertheless, these models appear to provide a sufficiently solid waste for construction of an aquaculture pond model, once the specifics of pond behavior are sufficiently well understood. Field data supporting conceptual notions of pond circulation, nutrient-nekton interactions, the importance of anoxia, toxic effects, etc. are presently scarce.

CONCLUSIONS

The literature review represented by this report resulted in identification of more than 200 references relevant to the principal topic, "Modeling the Hydromechanical and Water Quality Responses of Aquaculture Ponds." However, the great majority of these, as might be expected, focused on details of the behavior of lakes and reservoirs and their hydrochemical and biological properties and very few articles dealt specifically with mathematical modeling of aquaculture systems, per se.

While this source material will be valuable in the development of pond models, it appears that much is yet to be learned concerning the quantitative responses of small water bodies that are deliberately designed for aquaculture. In particular, there is a dearth of information on the hydraulics of ponds, e.g., effects of natural and man-induced circulation, mixing phenomena, stratification and detention time. Some guidance is available in the experience of model building for large lakes and reservoirs, but questions of scale are raised, e.g., Can this experience be transferred to the level of shallow pond systems? Indications are that it can, with appropriate attention to the fundamentals of hydroscience. The background provided in performance studies of detention basins for water and wastewater treatment should be useful as a starting point.

Water quality studies of small lakes, reservoirs and, in some cases, actual aquaculture ponds, provide a fair basis for qualitative characterization of water quality responses of pond systems. However, in this instance, also, experience is limited in so far as quantitation is concerned. Moreover, most studies deal only with a few constituents, for example, DO, BOD, or toxics, under unique circumstances; few consider the quality picture in a comprehensive way; that is, water quality-ecological interactions are not described quantitatively. More particularly, little attention has been given to temporal characterization of water quality in ponds, during the natural growth cycles of the cultivated species.

An area of obvious import to the efficiency of aquaculture is the interaction between the active aerobic strata in the upper part of the pond and the relatively quiescent benthos. Since this lower zone receives the excess of applied nutrient as particulate organic matter plus excreta, it is sure be highly active biologically. What role does it play, positively or negatively in the production of the primary species? What of the effects of anoxia? Are these effects mitigated by natural convective cycles or must they be adjusted by deliberate manipulation of the pond? Such questions, which depend on a better knowledge of pond water quality and its relation to the indigenous ecosystem, are in need of answers not yet found in the literature. They will be necessary in development of a suitable pond model.

Finally, as regards the pond ecosystem itself, most attention has been given to the primary species (for obvious reasons) at the expense of a more comprehensive treatment of the entire ecosystem. Certainly there are other species and trophic levels involved and, while these are usually secondary as far as the goal of aquaculture is concerned, the rest of the ecosystem may impact production of the primary species through control of habitat. An example is the growth of algal species which may restrict light penetration, thereby changing the overall heat energy balance, thus affecting stratification and mixing, enhancing benthic activity, giving rise to anoxia, etc. Under certain circumstances the role of this lower trophic level may strongly influence productivity. The

same argument may be made for the roles of bacteria and zooplankton.

Most aquaculture models tend to deal with the primary species directly and with the rest of the ecosystem indirectly, as a modifying effect, often assessed empirically. There is a need, the authors believe, to structure a pond model to include all these elements of the system, including water quality and the hydrodynamics that may under some conditions actually "drive" the model. At least a capability to consider quantitatively all relevant processes and to detemine sensitivity is needed. A mathematical model suited for this purpose is indicated. Its development is the logical next step in the line of research.

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A SURVEY OF THE MATHEMATICAL MODELS PERTINENT TO FISH PRODUCTION AND TROPICAL POND AQUACULTURE

by

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INTRODUCTION

The purpose of this Collaborative Research Support Program (CRSP) is to increase the production of protein in Less Developed Countries (LDCs) through the scientific study of tropical pond aquaculture. In a scheme designed to reach this goal, predictive models of biological processes will link practices and principles of pond aquaculture pertinent to tropical regions. This marriage will provide detailed understanding of the productive potential of tropical ponds and will create simple models of great utility to persons managing tropical ponds in LDCs.

The purpose of the planning grant for this CRSP is to provide a history of scientific research relevant to tropical pond aquaculture and to coordinate proposed research in the United States and in LDCs. Because the principles, practices, and predictive models of pond aquaculture are collectively too great a subject for one investigator to survey, these subjects were separately assigned to different researchers. The responsibility for the "state-of-the-art" survey of the predictive models and its synopsis was divided again. This report contains guidelines to coordinate proposed research on the predictive models of the dynamics of plankton and fish in tropical ponds. These guidelines do not specify models to the AID Aquaculture CRSP, but rather list a framework within which CRSP investigators can select the best model for their research.

Because ponds are small and because biology of tropical aquatic ecosystems is not well understood, the role of models to predict the productivity of tropical ponds has been very limited. Pond ecosystems can easily be altered to create relatively controlled experiments to provide information for management. With larger bodies of water, a resource manager does not have this ability and the information upon which he bases his management must come from models of the resource (Magnuson, 1973; Peterman, 1975). Because the culturalist need not model what he can describe through experiment on controlled environments, predictive models of pond aquaculture are few relative to the models of aquatic science that describe the productivity of large bodies of water.

The manager of tropical ponds pays a price for his dependence on results from descriptive experiments. These experiments are usually conducted at sites with several ponds as replicates at each site (e.g., Almazan and Boyd, 1978; Arce and Boyd, 1975; Bishara, 1978; Boyd, 1976; Haines, 1973; Stickney et al., 1979). The efficacy of specific aquaculture practices to boost production is tested by applying these practices to the ponds according to some rational scheme based on aquaculture principles. The experimental results are often reported in tabular form (e.g., Bishara, 1978; Boyd, 1976; Stickney et al., 1979) or in some kind of statistical format (e.g., Almazan and Boyd, 1978; Arce and Boyd, 1975; Haines, 1973) and then used by someone other than the experimenter and on sites other than those upon which the tests were made. This is one of the ways information is disseminated in the agriculture industry in the United States. By in large, this approach has worked well for U.S. Agriculture, but not as well for pond aquaculture. The application of experimental results from descriptive experiments to the other ponds is valid only as long as experimental conditions hold at these new sites. When results of experiments on pond ecosystems are used away from their site of origin, the accuracy of these results often breaks down; for example, the balance of bass-bluegill populations derived through experiments in Alabama does not hold for ponds farther north (Regier, 1962). Understanding is missing regarding the mechanisms that drive pond productivity. Without understanding, the results of descriptive experiments are too inflexible to conform to new sites and situations without repeating the descriptive experiments at each new site or for each new situation. U.S. Agriculture has overcome this problem through repeating experiments at many different sites under many different sets of environmental conditions. Agriculture is an old science and has had time to develop this approach. Although scientific tropical pond aquaculture does not have this advantage of age, it can use predictive models to speed its development and gain understanding of the mechanisms of pond productivity.

To manage tropical ponds for fish productivity, a dual approach is needed to both easily disseminate experimental results to managers in LDCs and to provide the understanding necessary to measure the precision of these results. In U.S. Agriculture, descriptive experiments still provide useful information because exhaustive laboratory and quantitative analysis help explain the observed precision of experimental results and their applicability to various situations not described by descriptive experiments.

Compared to U.S. Agriculture, the science of tropical pond aquaculture is still an infant. In time, tropical pond aquaculture will also mature as a science, and predictive models have an important role to play in that growth.

HISTORY OF PREDICTIVE MODELS IN TROPICAL POND AQUACULTURE

Most of this discussion will concern models that predict the productivity of temperate ponds and lakes. Because little is known about tropical aquatic ecosystems and models specific to tropical ponds are rare, temperate bodies of water must be the focal point of the following discussion. Always keep in mind that lakes are not ponds, temperate is not tropical, and these differences will alter the structure of the predictive models discussed below to some degree.

Predictive Models for the Fish Community

Predictive models of fish production from lacustrine ecosystems can be segregated according to the hierarchy of their focus: ecosystem, stock, or organism (Table 1). Models of whole pond ecosystems (hereafter called empirical models) are directly related to the descriptive experiments discussed in the Introduction where the ecosystem is treated as a "black box" with only inputs and outputs (Figure 1). Given certain inputs and conditions, a certain level of fish production is expected. In empirical models, each pond is assumed a replicate of the ecosystem. Building these models is akin to statistically building an experimental design with an ANOVA or a regression analysis (Liang et al., 1981). Regression analysis will provide some estimate of the experimental precision which is not directly available from an ANOVA or from a tabular report of experimental results.

Predictive models of stock production often separate stock dynamics into growth, mortality, reproduction, and recruitment of stock members (Figure 2). A stock is the portion of the animals of a single species in a single population that can be harvested (from Ricker, 1975). Information on the parts of stock models is derived through experiments that are usually independent of measuring fish production in the ponds (e.g., Bishara, 1978; Brown, 1970). For instance, some experiments may determine the effects of fertilizer on fish growth (Stickney et al., 1979), another experiment may investigate how pH affects mortality rates of fish (Menendez, 1976). Although production in stock models is mostly a function of age of the fish (e.g., Deriso, 1980; Jensen, 1973), environmental influences can be incorporated into these models (e.g., Bakun and Parrish, 1981; Gatto and Rinaldi, 1976; McKelvey et al., 1980). When information on fish growth, fish survival, and environment are combined, the result can be an estimate of production to compare against in situ measurements of production. Stock models that focus on fish tacitly assume that fish and other pond organisms little affect each others dynamics. When this assumption is false, precision of experimental results declines. Also, with more parts than the empirical models, stock models have more parameters to estimate (Figure 3). But because stock

Table 1

THE HIERARCHY OF EMPIRICAL, STOCK, AND MECHANISTIC MODELS TO PREDICT FISH PRODUCTION FROM TROPICAL PONDS

Empirical Models

$$P = f(\underline{X})$$

Stock Models

$$P = f\{g_1(\underline{X}), g_2(\underline{X}), \ldots g_m(\underline{X})\}$$

Mechanistic Models

$$P = f[g_1\{h_{11}(\underline{X}), h_{12}(\underline{X}) \text{ --- } h_{1n}(\underline{X})\}, g_2\{h_{21}, h_{22}, \text{ --- } h_{2n}\}, \ldots$$

$$g_m\{h_{m1}, h_{m2}, \text{ --- } h_{mn}\}]$$

where

P = production

f, g, h = functions in the models

$\underline{X}$ = a vector of inputs (e.g. x_1 = weight of fish stocked, x_2 = weight of nitrogen fertilizer used, etc.)

models require a better understanding of the internal mechanisms of pond production, they are more relevant to a wider variety of ponds than are empirical models. For instance, growth by a fish in one pond will be similar to growth of a fish of the same species in another pond, an insight that can be used in pond after pond to estimate fish production without experiments on new ponds.

In stock models, recruitment, growth, survival, and reproduction somewhat explain the variation in production seen in the descriptive experiments from which empirical models are derived. Unfortunately, the processes in the stock models are still too simple to incorporate a wide range of aquaculture practices and still gain much understanding of the underlying biological and physical mechanisms of pond productivity.

The predictive models that focus on organisms (hereafter called mechanistic models) describe biological and environmental processes on a finer scale than do the stock models (Figure 4). Again, experiments to model aquaculture principles are independent of the pond ecosystem, and their modeled results are summed to provide estimates of productivity. Growth is modeled as the antagonism between respiration and ingestion (e.g., Caulton, 1978; Ursin, 1967); mortality is the sum of disease, predation, starvation, and competition (e.g., Smith, 1976); and reproduction and recruitment are functions of growth, fecundity, and survival (e.g., Jackson, 1979). Although mechanistic models require estimates for many parameters and many independent experiments to get them, these models do link pond practices to pond production by modeling the principles of pond aquaculture. Even more so than do stock models, mechanistic models can explain the fish production seen in the descriptive experiments as functions of aquaculture practices. But mechanistic models are complex syntheses of what is known of the pond ecosystem, and are therefore more difficult to build and more difficult to use in management than are the simpler empirical and stock models. More than the other types, mechanistic models are abstractions of what the modeler feels are the important principles in the ecosystem. Therefore, testing the validity of these models by comparing their predictions of productivity against those from field experiments is imperative (Kerr, 1976).

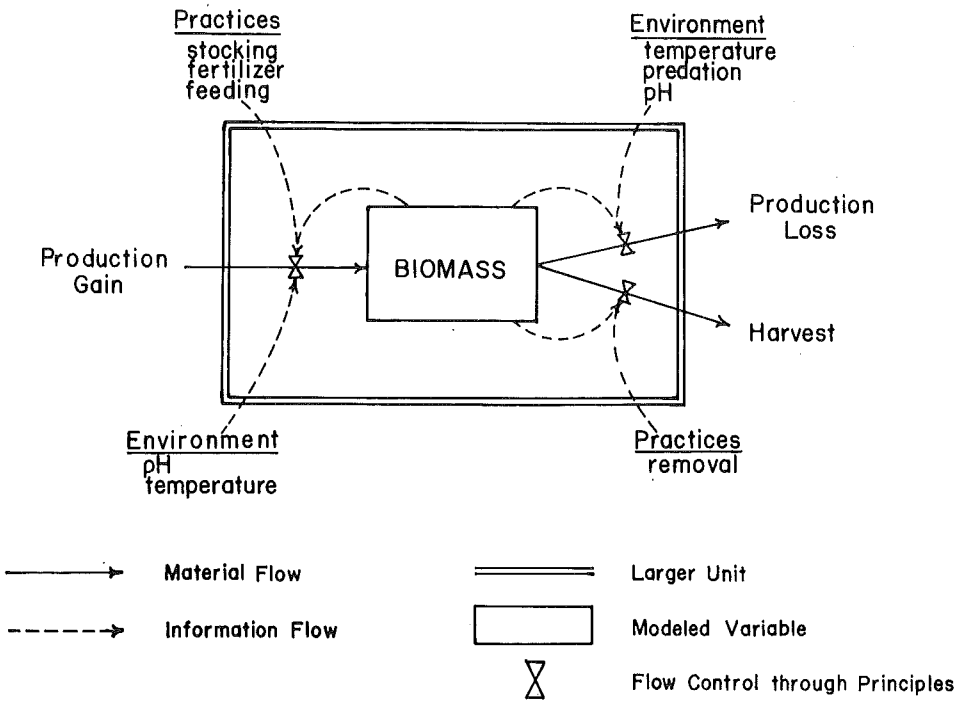

Figure 1

Schematic of a hypothetical empirical model with symbols according to Patten (1975). Biomass flows into the larger unit (the pond ecosystem) through production and flows out through harvest and mortality. Aquaculture practices and environment (physical, chemical, and biological) control inflows and outflows of production through aquaculture principles.

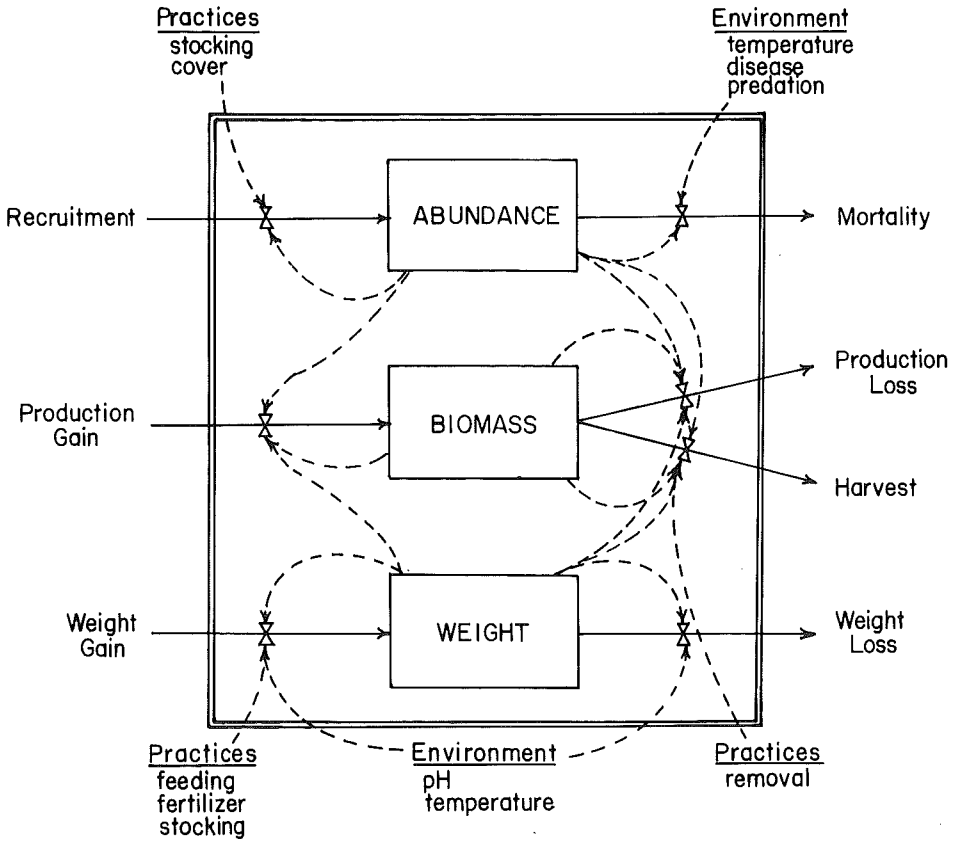

Figure 2

Schematic of a hypothetical stock model. Symbols are defined in Figure 1. The large, double lined box represents the conceptual boundaries of the pond ecosystem.

Predictive Models for the Plankton Community

Predictive models of plankton production in ponds, like those for fish production, are classed according to their resolution (Table 1 and Figure 2). Published empirical models predict productivity as a function of morphoedaphic factors (e.g., Ryder et al., 1974), nutrient-loading (e.g., Dillon and Rigler, 1974a, 1974b), or a "super-organism" whose dynamics depend on light, temperature, and nutrients (e.g., Fee, 1973a, 1973b; Jassby and Platt, 1976). Stock models of plankton production express phenomena that concern groups of organisms and sum their dynamics in the model (e.g., Patten and Van Dyne, 1968) or in something less than the sum if competition and or predation occur within the plankton community (e.g., Lynch, 1977). The tradeoffs between using stock and empirical models are the same as in modeling fish production, only more so because of the greater diversity in the plankton community. The finer the resolution of the model, the more numerous are its parameters, the greater the understanding it provides, and the more difficult it is to use.

Obviously, the fine resolution of the mechanistic model demands that many taxa be modeled. Instead of modeling taxa, modeling functional-groups, such as planktivores, benthic predators, etc., can reduce the bookkeeping in these models (e.g., Lehman et al., 1975). However, such shortcuts can go but so far. Because competition, predation, respiration and other processes occur for plankton as for fish (e.g., Dodson et al., 1976; Lynch, 1977), these processes must be included in the mechanistic models.

Most predictive models concern phytoplankton and not zooplankton. Although the same modeling philosophies can be used for both types of plankton, zooplankton are far more difficult to model as a group because their dynamics are affected by the trophic levels below and above them. The dynamics of primary production drives zooplankton production while vertebrate predators alter zooplankton diversity. Empirical models have generally been poor predictors of zooplankton dynamics (see Buzas, 1971). Stock and mechanistic models are extremely rare, although a few principles of zooplankton productivity have been modeled [e.g., stock models: Caswell (1972), Taylor and Slatkin (1981); mechanistic models: Confer and Blades (1975), Peters (1975)].

Because benthos production is difficult to model when it is separated from those factors that affect it, few strictly benthos models exist. Vertebrate

predators and omnivores affect benthic production as do allochotonous organic materials (e.g., Hall and Hyatt, 1978) and detritus settling from the plankton community (e.g., Cherry and Guthrie, 1975; Eggers et al., 1978; Hall and Hyatt, 1974). However, some principles of pond aquaculture relative to stock and mechanistic models of benthos have been modeled (e.g., Frost, 1972; Hall and Hyatt, 1974; Ware, 1973).

RECOMMENDATIONS

For the AID Aquaculture CRSP, both empirical and mechanistic models should be used to study tropical pond aquaculture. Empirical models will provide the materials for overseas management of tropical ponds in the LDC's. Also, the mechanistic models can be validated against the descriptive experiments upon which the empirical models are based. Mechanistic models will provide insight to the precision in the empirical models and direct future experiments to improve that precision. Because the advantages and disadvantages of stock models are repeated if both empirical and mechanistic models are used, the AID Aquaculture CRSP need not use stock models.

Because the empirical models are site-specific, they must be constructed for each of the overseas projects on management of tropical ponds. These models should be based on descriptive experiments like those in temperate pond aquaculture (e.g., Haines, 1973), but unlike many of these experiments, simply reporting their results is not enough. Results must be rigorously analyzed with ANOVAs and/or regression analysis to provide estimates of experimental precision. The pond manager in the LDC must know the probability of getting undesired results from any particular set of aquaculture practices. Great care should be exercised to develop an experimental design which will provide an analysis of precision through adequate replication at each site.

The manager in the LDC should be presented with this modeling in its simplest possible form (see Peterman, 1975), either as tables of inputs (fertilizers, stocking rates, etc.) with the expected levels of production, or as a simple model on a hand-held

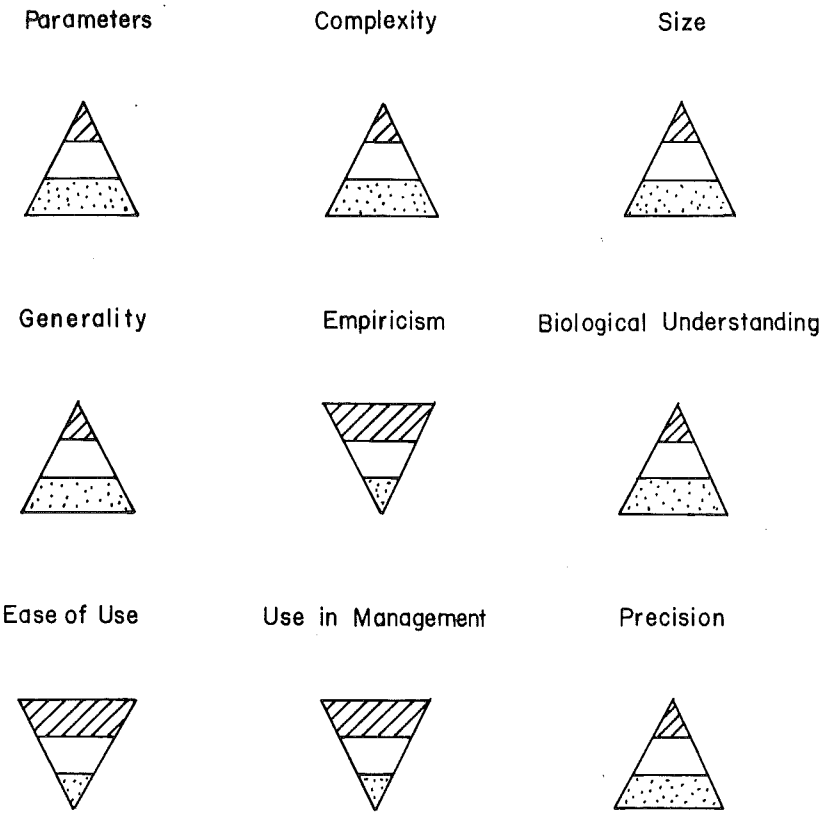

Figure 3

Relative merits of three approaches to modeling production in tropical ponds: empirical models (the lined area), stock models (the blank area), and mechanistic models (the stippled area). Area within triangles correspond directly to the spectrum of few to many, little to much, small to large, etc.

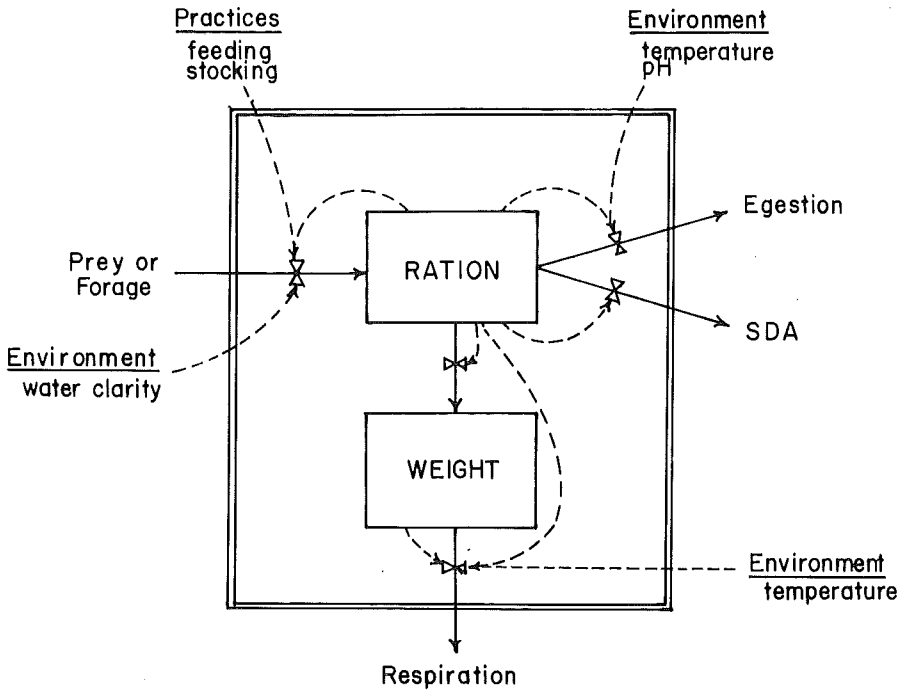

Figure 4

Schematic of a submodel of growth in a hypothetical mechanistic model. The large, double-lined square corresponds to the variable weight in Figure 2. Symbols are defined in Figure 1.

calculator or on a small computer that will provide the same service. If the empirical model is to be used in the LDC for management, it should be stochastic to represent the precision of aquaculture practices to produce desired yields.

The mechanistic models and their results should not be used for management in LDCs, but should be used to improve empirical models (see Larkin, 1978). The mechanistic models should explain the same data with the same inputs as do the empirical models, but unlike the simpler models, should link production directly to aquaculture practices through modeling aquacultural principles. And because mechanistic models are based on processes, these models can and should be tested with inputs other than those used in the field experiments, then validated against new descriptive experiments with these inputs. Mechanistic models should be deterministic and used to explore the imprecision in the empirical models through this procedure.

Both modeling efforts should describe the important parts of the ecosystem and the physical environment in tropical ponds. Some comprehensiveness is implicit in the empirical model; it includes fish, plankton, benthos, and physical environment in a single "black box." In the mechanistic model, these processes and factors must be inserted into the model. Unlike many terrestrial ecosystems, the different trophic levels in aquatic systems can be interdependent and virtually impossible to model separately (Patten, 1975).

The physical and chemical environment in ponds drives the ecosystem and is somewhat driven by it. Therefore, the mechanistic models must include models of the physical and chemical environment of ponds.

The proposal for the AID Aquaculture CRSP specifies four types of ponds as study sites: coolwater ponds at high elevations, brackish ponds, ponds with their production augmented with energy and/or fertilizers, and ponds with little or no such inputs. Each type of pond requires its own modeling effort, at least during the early stages of the Aquaculture CRSP. Because the empirical models will be time- and site-specific, they must be built for each site. On the other hand, mechanistic models are not bound to particular sites, but to particular principles. If these principles are universal among the studied ponds, then all mechanistic models will have similar components. As different mechanistic models from different sites are compared, some components of these models common to all four types of ponds can be combined and the modeling effort simplified (see Holling, 1966).

GUIDELINES FOR PROPOSALS

1) Fish and plankton production in each type of pond studied for the AID Aquaculture CRSP should be predicted with two models: a stochastic empirical model based statistically on field data and a deterministic mechanistic model based on the same information from these ponds and from independent experiments.

2) Both kinds of models should be subject to experimental validation through implementing aquaculture practices on modeled ponds.

3) The stochastic empirical models should be capable of operating on simple computing devices for use in LDCs.

4) The plankton, benthic, and the fish communities along with their physical and chemical environment must be modeled as a unit for each pond.

5) The empirical models (or their results) should be used in pond management in LDCs. The mechanistic models should not.

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LITERATURE SUMMARY

The following index and literature summary describe examples of predictive models used to study pond and lake productivity. The citations complement those in the preceding REPORT.

The following summary does not represent all the literature on predictive models, but does give a comprehensive menu of that literature. Only models of pond or lake ecosystems, models of animals or plants from these ecosystems, and models of biological principles germane to these ecosystems are included in the summary. Models of nutrient loading are considered ecosystem models and are included. No models of stream, ocean, or estuarine ecosystems are listed except those based on principles that are germane to pond ecosystems. And although the literature on the stock models of fisheries is extensive, citations on these models are few because ecosystem and mechanistic models are recommended over stock models for research of the productivity of tropical ponds. However, stock models of plankton are included. Often, the mechanistic models referenced in the index describe one, or a few, principles of pond aquaculture and must be joined with complementary models to create a single mechanistic model of pond production. Some citations are included in the summary for their general descriptions of aquatic ecosystems and their predictive models.

The index is an attempt to separate the citations in the literature summary by subject matter. Because differences among stock, ecosystem, and mechanistic models are often a matter of perspective, some models in the index may not fit with readers' judgments.

INDEX

Subject

Fish: 7-9, 12, 17, 22-24, 33, 39-44, 47, 56-58, 61, 62, 66, 72-73, 75, 76-78, 80-81

Phytoplankton: 4-6, 21, 25-28, 34, 38, 45, 50-51, 54-55, 57, 62, 64-65, 69, 76-79

Benthos: 57, 67

Nutrient-loading: 13-14, 19-20, 37, 53, 65, 69

Other Organisms: 2-3, 10, 57

Lakes: 4-5, 13-14, 17, 19-20, 25-28, 37, 39-43, 55, 57, 65, 69

Ponds: 9, 17, 80

Other Bodies of Water: 6-7, 10, 38, 58, 62, 77

Ecosystem Models: 4-5, 10, 21, 25-28, 31, 34, 38, 45, 47, 54-55, 69

Stock Models: 11, 29, 30, 50, 64, 66, 68, 70-71

Mechanistic Models: 65, 74-78

- Reproduction: 18, 42-44, 57
- Respiration: 9, 22, 33, 39-44, 49, 57, 62, 73, 80
- Digestion: 59, 80-81
- Predation-Grazing: 1-3, 6-7, 15-17, 23-24, 32, 35-36, 39-43, 49, 51-52, 56-58, 67, 75-77, 80
- Competition: 1, 53, 61
- Distribution: 2-3, 15-16, 32, 39-41, 72

General Models: 46, 56-57, 63, 65, 70, 74, 79

- Growth: 12, 29-30, 73, 79
- Mortality: 8-9, 66, 68, 71, 73, 75

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PART 5

POND AQUACULTURE : THE FUTURE

POND AQUACULTURE: THE FUTURE

After reading the papers presented in the first four parts of this report, it should be apparent that to develop a clear understanding of the interrelationships that govern the productivity of pond culture systems is an ambitious undertaking. To accomplish such an understanding will require the coordinated effort of many dedicated researchers over a long period of time. Emphasis should be placed on the word coordinated, for without the coordinated efforts of researchers throughout the world there is little hope that a unified theory can be developed.

One of the purposes of this state-of-the-art report was to develop information that could be used to formulate an aquaculture CRSP that would meet the objectives of the Title XII legislation and would lead to the development of unified theory. Therefore, the objective of this concluding part is to present a brief summary of the findings presented previously and to suggest guidelines that can be used to develop an aquaculture CRSP.

SUMMARY

The principal findings of the state-of-the-art survey are as follows:

1. Much of the information on pond culture systems is descriptive as opposed to quantitative. Thus, while the literature provides general operating guidelines for the operation of pond culture systems, it is of limited predictive value. Additionally, because descriptive data can not be analyzed statistically, many generalizations found in the literature must be considered speculative at this time.

2. Among the quantitative data presently available, a lack of standardization in experimental design, data collection, and analysis renders the existing data base of limited utility in predicting the performance of pond culture systems. Most of the quantitative data is found in technical reports describing a limited number of observations over a limited time period. Consequently, much of the data lacks statistical precision, is site specific, and the reproducibility of the results is subject to question. However, the existing information base can be utilized as a starting point to formulate testable hypotheses about the performance of pond culture systems.

3. Among the myriad technical questions about pond culture systems, there is a unifying question: how do physical, chemical, and biological processes interact to regulate the productivity of these systems? The description of these processes involves the overlapping disciplines of fish production, water chemistry, and physical and biological limnology.

4. In considering pond culture practices, the number of correlations increases exponentially with the number of variables observed. A cost effective approach to researching the principles of pond culture systems must initially address the limited subset of correlations which appear to be most important in understanding the underlying principles. This list can become more comprehensive as the processes which constrain the efficiency of pond culture systems are defined.

5. If the CRSP is to employ predictive mathematical models as management and research tools in improving the efficiency of pond culture systems, additional model development will be required. Numerous mathematical models have been developed to describe processes in various aquatic systems such as lakes and wastewater treatment systems. Although the mathematical tools needed for the description of pond culture systems may be adapted from these models, there are apparently no existing mathematical models entirely satisfactory for use in the aquaculture CRSP. Additionally, because one of the purposes for developing descriptive models of pond culture systems is to provide predictive models that can be used as management tools in the field in the LDCs, the hardware and software requirements for utilizing such models must be reduced to allow application of the models to field calculating equipment.

PLANNING GUIDELINES

Guidelines which follow from this state-of-the-art survey and the country visits that have been used in planning the aquaculture CRSP are as follows.

1. Involve the existing host country infrastructure in the CRSP to the fullest extent possible.

The primary intent of the aquaculture CRSP is not to introduce a new research program into the participating countries. Rather, it is to strengthen the country research capabilities to pursue research of global interest by providing additional technical competency and logistic support.

2. The technical goal of the aquaculture CRSP is to describe quantitatively the physical, chemical, and biological principles of pond culture systems.

In an aquacultural context, the corollary to this guideline is to understand how fish culture practices influence the physical, chemical, and biological processes occurring in pond culture systems.

3. In understanding the principles of pond culture systems, it is essential to distinguish between site specific and general considerations.

If technologies developed under the aquaculture CRSP are to be utilized to replicate the most efficient systems over a broad geographic range, coming to terms with site specificity is of paramount importance.

4. In understanding the principles of pond culture systems, it is essential to distinguish between general principles applicable to all production systems and principles which apply only to specific systems.

In addition to the four systems previously identified for investigation, the principles of fry production systems should be investigated concurrently whenever possible. The geographical application of the various systems must also be addressed.

5. Wherever possible, CRSP research activities should employ standardized experimental designs, methods, and data collection and analysis.

Quantitative standardization is essential if findings from the aquaculture CRSP are to be utilized over a wide range of applications and locations.

6. The number of variables investigated at any particular time must be limited.

The quality of the data collected is more important than the quantity. Undertaking overambitious experiments compromises the quality of results by overtaxing the technical work force. In the design of experiments, the correlations to be tested must be specified, and data collection limited to those observations needed for these specific tests.

7. The output of the aquaculture CRSP must be applicable to improving the efficiency of pond culture systems in LDCs.

Operating guidelines resulting from the CRSP must be applied by persons not formally affiliated with the CRSP. Thus, quantitative outputs, including predictive models, must be available in a form that can be applied in the field. Additionally, oversophistication must be avoided in selecting methods for measuring the processes occurring in pond culture systems.

WHERE DO WE GO FROM HERE?

The CRSP is now implemented with six projects distributed over three continents. Each project consists of replicated field plot experiments conducted on a standardized experimental design. The statistical design will allow direct quantitative comparisons to be made between and within locations. The intent of the first cycle of experiments, presently in progress, is to develop comprehensive physical, chemical and biological baseline data for each location. Once these baseline data are established, responses to various treatments can be investigated. Additionally, critical research needs will become increasingly apparent as the experiments proceed.

As the CRSP progresses, researchers will have a tool which has never before been available; a standardized quantitative data set which will become more comprehensive with time. Although the number of work locations is limited, a variety of aquaculture systems and geographic and climatic situations are included. It is hoped that as this research effort gains momentum other investigators across the world who share with us our dedication to understanding the dynamics of pond culture systems will contribute to and share our expanding data set, thereby joining with us in a global assault on the problems of developing aquaculture. Working together, collectively and systematically, we can accelerate the development of a unified theory and hasten the arrival of a genuine aquaculture technology.