PRECISION AGRICULTURE THROUGH AGROECOLOGICAL APPROACH AND MATHEMATICAL MODELING

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Abstract. Precision agriculture is a modern farming management concept using digital techniques to monitor and optimize agricultural production processes. The agroecological approach focuses on the interactions between plants, animals, soil organisms, people, and the environment. It aims to optimize the use of natural resources, enhance biological processes in the soil, and improve biomass, nutrient, carbon, and water cycles. The paper deals with the basic dependencies between some of the factors determining nutrient processes in the soil and the need for fertilizing crops with the main nutrients as components of precision agriculture. An approach to modeling is proposed that meets several requirements and criteria. Mathematical models for calculating fertilizer recommendations give the amounts of the following nutrients: nitrogen, phosphorus, and potassium, required for the target yield on each particular field. Guidelines for improving and refining models for determining the need for fertilizers are given, taking into account all factors governing nutrient flows in the soil.

Keywords: precision agriculture, agroecological approach, mathematical modeling, fertilizer requirements

INTRODUCTION

Definitions

The European Parliament's report on "Precision agriculture and the future of farming in Europe" defines precision agriculture as: "a modern farming management concept using digital techniques to monitor and optimize agricultural production processes". The key point here is optimization. Instead of applying an equal amount of fertilizers over an entire field, precision agriculture involves measuring the within-field soil variations and adapting the fertilizer strategy accordingly. This leads to optimized fertilizer usage, saving cost, and reducing the environmental impact (AgroCares, 2020). Precision farming and precision agriculture are generally regarded as the same thing. However, the term precision agriculture, often abbreviated PA, is more widely used.

Precision farming is a systems approach to managing soils and crops to reduce decision uncertainty through better understanding and management of spatial and temporal variability. It should be viewed as a systems approach to crop production in which the goal is to reduce decision uncertainty through better understanding and management of uncontrolled variation. Expertise from many disciplines is utilized, often also information technology, to bring data from multiple sources and scales to bear on decisions associated with crop production (Dobermann et al., 2004).

There are three main definitions of the term "agroecology": as a scientific discipline, as a movement, and as a practice. Despite the existence of different approaches and definitions, the new views and dimensions brought into agroecology as a scientific discipline will help facilitate the efforts to respond to the actual challenges of agricultural production, because of increasingly applied systems

thinking and interdisciplinary research approaches (Wezel et al., 2009).

Agroecological approaches are inspired by natural ecosystems. They focus on the interactions between plants, animals, soil organisms, people, and the environment. This means that they optimize the use of natural resources, enhance biological processes in the soil, and improve biomass, nutrient, carbon, and water cycles. This allows producers to reduce external inputs and costs while improving the health and resilience of plants and animals (EIP-AGRI, 2020).

Essential details

Precision Agriculture (PA) is a whole-farm management approach using information technology, satellite positioning data, remote sensing, and proximal data gathering. These technologies have the goal of optimizing returns on inputs whilst potentially reducing environmental impacts (EU-DG IP, 2014). Research and studies are necessary to improve the knowledge and cost-benefit aspects of PA, especially concerning the environmental impact. An important application of precision agriculture in arable land is to optimize the use of fertilizers, starting with the three main nutrients nitrogen (N), phosphorus (P), and potassium (K). In conventional farming, these fertilizers are applied uniformly over fields at certain times during the year. This leads to over-application in some places and under-application in others.

A major legal challenge associated with the systematic introduction of precision agriculture in Europe largely stems from the way of processing large amounts of information (mostly agronomic data) accumulated through a variety of technical means that is of high importance to farmers and farm organizations, and the use of decision algorithms (Kriticos, 2017).

Precision agriculture system (PAS) management would increase crop production and crop profitability, decrease crop production variability

and improve soil and water quality over the conventional uniform management of the years before PAS (Yost et al., 2017). The authors conclude that future analyses will be conducted to evaluate a suite of potential benefits of PAS including profitability, soil quality, and water quality. The goal of precision agriculture research is to define a decision support system (DSS) for whole-farm management to optimize returns on inputs while preserving resources (Wikipedia, 2020).

The simplest plant ecosystem can be defined as one plant organism and the environment it inhabits. Based on this concept we consider agroecosystems as plant ecosystems that are managed and exploited by man. These are characterized by four groups of factors: biological, meteorological, soil, and anthropogenic. In agroecosystems, the crop and its non-living (abiotic) environment are connected and continuously interacting with each other.

The agroecosystem concept is regarded as an epistemological tool for creating an ontology or representation of agriculture based on a system view. Development of sustainability indicators is considered a crucial step of inquiry for providing elements of assessment, evaluation, and anticipation of solutions for both farm design and management, and land-use policy (Caporali, 2015).

Agroecology can be defined broadly or narrowly. Loosely defined, agroecology often incorporates ideas about a more environmentally and socially sensitive approach to agriculture, one that focuses not only on production but also on the ecological sustainability of the productive system. At its most narrow, agroecology refers to the study of purely ecological phenomena within the crop field, such as predator/prey relations, or crop/weed competition (Gold, 2007). The results of agroecological studies, generated on the plot, field, or farm level, cannot always readily be generalized to the regional, national, or global level relevant for decision-makers. Because of this gap, the results are often misinterpreted or not used in the decision-making process (Dalgaard et al., 2003).

The acceleration of ecological crises has driven a growing body of thinking on sustainability transitions. Agroecology is being promoted as an approach that can address multiple crises in the food system while addressing climate change and contributing to the sustainable development goals (Anderson et al., 2019). Agroecology is fundamentally different from other approaches to sustainable development. It is based on bottom-up and territorial processes, helping to deliver contextualized solutions to local problems. Although the prevalence and prominence of agroecology are growing in Canada, its presence is

still small and the support for its development is limited (Isaac et al., 2018). Canadian agricultural policy is seemingly shortsighted, particularly in comparison to other countries that are actively integrating agroecology into regulatory frameworks (e.g., Brazil, Cuba, France, and Sweden).

In their Review (Gallardo-López et al., 2018), according to the number of research documents and to the percentage of uses of the concept, the authors identified three groups of countries in Europe. A little group with initial contributions completely directed to science; a second group with a tendency to science, followed by practice, and a little marginal to movement; and a third and more prolific group, where the practice was predominant, followed by science and to a lesser degree as a movement. If a technology works to improve productivity for farmers and does not cause undue harm to the environment, then it is likely to have some sustainability benefits. Agricultural systems emphasizing these principles also tend to be multi-functional within landscapes and economies (Pretty, 2006).

Agroecological approaches look at the entire agroecosystem and the multiple relationships within it, rather than addressing each component separately as with most conventional agricultural research (Silici, 2014). While obtaining high and stable yields is important to all farmers, agroecological practices seek to optimize, rather than maximize, production (and profits). Measuring achievements in terms of yield optimization and environmental benefits may prove complex in practice. There are many examples of benefits when applying the agroecological approach (Nicholls et al., 2016; Sinclair et al., 2019).

Crop programming is the development of a set of technological techniques for optimizing controlled environmental factors for obtaining a given high level of field crop yield. The methodological basis for programming agricultural crops are ten principles defined by academician I.S. Shatilov (Shatilov & Chudnowsky, 1980).

This article aims to present the basic dependencies between some of the factors governing nutrient flows in the soil and the needs for fertilizing crops with the main nutrients nitrogen, phosphorus, and potassium – as components of precision agriculture.

MATERIALS AND METHODS

New technologies are rapidly emerging and are revolutionizing farming in the next decade. If digital agriculture is really to offer solutions to problems like the environmental impact of agricultural

production, then one of the biggest challenges is the adoption of technological solutions. Climate change, loss of soil fertility, depletion of water and other resources, and the vulnerable genetic basis of industrial monocultures with expanding use of chemical agents are damaging world food security. This awareness is now one reason (among others) that after a long period of decreasing investment in agricultural research, recent years have seen a much stronger commitment from national and international stakeholders for research into agriculture and the means to make it more sustainable (Brewster & Willener, 2018).

The separate processes in crop yield formation must be covered and modeled while taking into account their characteristics and mutual dependencies. Optimization of yield formation is possible only when each process is modeled adequately with respect to its

hidden laws and the respective models are in correct relationships with each other. Due to its complexity yield formation cannot be described using a single, however sophisticated, mathematical model. The optimal management of the whole production process requires the creation of a system of models (Fischer & Richter, 1970).

The real production system in plant production consists of two main subsystems: a manageable subsystem (the agroecosystem) and a control subsystem (the anthropogenic factor). Fig. 1 presents the main elements of the agroecosystem: soil, sowing, and atmosphere. The inputs of the system are the material, energy, and information flows, while the output is the yield with its quantitative and qualitative characteristics. The control subsystem is connected with a feedback contour and includes the elements of economy and technology (Sadovski, 2018).

Fig. 1. The real system

The management of production processes in agriculture is possible only if accurate and comprehensive information on the crops, their development, and the external environment is promptly available. Based on this information, using mathematical models and computer technology, problems can be solved to provide support in making applicable, rational, and optimal decisions at three hierarchical levels:

- Long-term planning and management of tasks with relevance for 5 – 10 or more years.
- Technical and economic planning and management of tasks within one business year.
- Operational planning and management (agricultural monitoring) to solve tasks related to yield formation during the vegetation period.

The immediate goal of agronomic research should be the development of an integrated automated system for the management of the

technological processes in plant production. The creation of a cybernetic system for yield management would turn the vision for "an electronic agronomist" of the academician A. Yoffe from the late 1950s into reality (Zhukovsky and Chudnovsky, 1973).

According to Glogov (1984), there are two main problems in agriculture as a science and a production process:

The first is to plan on a probability basis the actually possible yield for each specific field in a crop rotation system;

The second is to develop technologies for obtaining the planned yields which also include the management of yield formation during the growing season. From the viewpoint of economic cybernetics, this is to define the two main goals in the management cycle of material production: planning of production and management of the production process.

Accurate data on yield quantities can be obtained after the growing season and harvesting of the crops. The tasks of planning and management in agriculture, however, require a preliminary assessment of these quantities.

There are two main approaches to yield forecasting during the growing season:

- The subjective approach is based on visual observations of the state of the sowing or a general prediction of yield quantity. It includes the method of expert assessment.

- The objective approach is based on measurements of different variables. The methods of this approach can be classified into three groups. The first group includes direct measurements of the sowings, while the second uses remote aerial photographs or satellite imagery.

The third group of objective methods uses mathematical models and takes into account the factors with a significant impact on the final yield (biological, meteorological, soil, agrotechnical). Many such methods for yield forecasting have been developed for the main agricultural crops (Zhuchenko et al., 1980). The majority represent empirical regression models taking into account a limited number of factors. They lack a unified methodological basis, as they do not use the system approach in agroecosystem analysis.

The construction of a mathematical model must satisfy two important criteria (Ruzavin, 1984):

First, the model must be adequate, i.e. to correspond to reality. The extent of this correspondence can be different, but in any case, the model must provide an approximately true reflection of the modeled real object, process, or phenomenon.

Second, the model must be relatively simple and find a solution to the given problem within acceptable time limits with sufficient accuracy.

The success of mathematical modeling depends on the skillful combination of these two criteria. The leading rule must be the well-known "principle of simplicity" formulated in the 16th century by William of Ockham: "Entities are not to be multiplied beyond necessity" or "It is futile to do with more what can be done with fewer." (Ockham, 1964). Our approach satisfies all the above-mentioned requirements.

The materials used for this study are data from published long-standing field fertilizer experiments conducted on the experimental fields of the N. Poushkarov Institute of Soil Science, which are currently organized in a database (Petkova et al., 2019), and the results of basic research by several authors (Garbouchev & Sadvski, 1978; Milcheva, 1985; Neikova-Bocheva, 1985). The methods follow the methodology outlined above and include the methods of

Mathematical Agronomy used by the author (Sadvski, 2018).

RESULTS AND DISCUSSION

The relationships and interactions between output (target) and input (explanatory) variables may represent agroecological phenomena that *are both multivariate and non-linear* (Delmotte et al., 2011). Furthermore, whether or not researchers regard a specific farmland area as an intricate agricultural ecosystem. Such a farming area could well be an intrinsically complex ecological system, in which several variables and factors often directly influence food production. Thus, researchers may need to use multivariate statistical methods and non-linear mathematical models for analyzing agroecological phenomena, and these techniques are considerably more complex than classical statistical procedures such as analysis of variance and multiple linear regression.

A significant error in a many of the known models is that the argument X on their right-hand side represents the introduced quantity of mineral fertilizer, without taking into account the quantity of nutrients already available in the soil.

The following theory expresses the quantity of a given nutrient X as a sum of the initial level of the nutrient X_0 and the quantity introduced with fertilizers F :

$$X = X_0 + F.$$

Some authors consider X_0 as the quantity of the nutrient in the soil which is readily available to plants in a form, equivalent to the applied fertilizers (Derzhavin & Rubanov, 1975; Rubanov, 1978) and therefore use the term soil equivalent.

The main equation represents yield as an intrinsically non-linear function of macro element fertilization and has the expression

$$Y = f(X) = a(X_0 + F)^b \exp[c(X_0 + F)].$$

This multiplicative equation is a composition of a power function and an exponential function and it is used to determine the yield depending on the nutrient to be applied and its quantity already available in the soil. Thus, it contains the mechanism of homeostatic feedback (Sadvski, 1984a).

The model for calculating fertilizer recommendations gives the amounts of the following nutrients: nitrogen (N), phosphorus (P), and potassium (K), required for the target yield on each particular field. The nitrogen fertilizer requirements are determined based on the balance sheet of available N in the soil, nitrogen uptake by plants, and the coefficient of N utilization from fertilizers (Garbouchev, 1977).

Calculation of N rate, where:

$$RN_{ij} = (a_0 + a_1 \cdot Z_N + a_2 \cdot Y_i) \cdot c_j$$

RN = rate of nitrogen in kg/ha; i - code number of the field; j - soil type or soil group; Z_N - rate of N

supplying ability; Y_i - target yield; c_j - correction coefficient; a_0, a_1, a_2 - regression coefficients.

Example: Wheat grown on leached chernozem

$$Z_N = 30; Y_i = 4\,800 \text{ kg/ha}; c_j = 2.04.$$

$$RN = (9.6743 - 0.0793 \times 30 + 0.0122 \times 4\,800) \times 2.04 = 134.3 \text{ kg/ha}$$

Theoretical considerations and results of field fertilizer experiments support the thesis that phosphorus and potassium optimum levels have greater agronomic efficiency than annual fertilization and have the advantage that it applies to soil fertility and all crops. Rates of P and K are aimed at building up optimum levels of nutrients in the soil (Sadovski, 1984b; Milcheva, 1985; Neikova-Bocheva, 1985).

Calculation of P_2O_5 rate:

$$SP_{ij} = A_j \cdot \exp(B_j \cdot Z_i^2)$$

$$RP_{ij} = (SP_{ij} / T + U_{ij}) \cdot k_j$$

where:

SP_{ij} - sorption capacity (amount required to reach optimal concentration of 0.2 mg/kg P in 0.01 mol/l $CaCl_2$); Z_i^2 - available P established by soil testing; A_j, B_j - regression coefficients; RP = rate of phosphorus in kg/ha; T - time to build up a phosphorus level; U_{ij} - amount of P taken up by crop; k_j - coefficient of P ageing.

Example: Wheat grown on leached chernozem

SP = 816; T = 12 years; Y = 4 800 kg/ha; U = 48; $k_{ag} = 1.101$.

$$RP = (816/12 + 48) \times 1.101 \times 10 = 127.7 \text{ kg/ha}$$

Calculation of K_2O rate:

$$RK_{ij} = U_{ij} / k_1 + (Z_j - Z_i) \cdot k_2 / k_3 \cdot T$$

where:

RK = rate of potassium in kg/ha; U_{ij} - the amount of K taken up by crop; k_1 - coefficient of K utilization; k_2 - coefficient of calculation for the bulk weight of plow layer per hectare in tone; k_3 - coefficient of the effect of the newly applied K fertilizer; Z_j - optimal level of K required; Z_i - available K established by soil testing; T - time to build up a potassium level.

Example: Wheat grown on grey forest soil

T = 12 years; Y = 5 000 kg/ha; U = 50; $k_1 = 0.80$; $k_2 = 3.0$; $k_3 = 0.60$; $Z_j = 12$; $Z_i = 9$.

$$RK = 11.5 / 0.80 + (12 - 9) \times 3 / 12 \times 0.60 = 15.625 \times 10 = 156.25 \text{ kg/ha}$$

The mathematical models presented here do not pretend to cover all important factors that influence the amount of the fertilizer rates for these elements. A more complete description of the factors affecting the nutrient flows of substances in the soil and which must be taken into account when determining fertilizer rates of nitrogen, phosphorus and potassium are presented in Table 1 (Roy et al., 2003).

Input		Output	
IN 1	Mineral fertilizers	OUT 1	Harvested product
IN 2	Manure	OUT 2	Crop residues
IN 3	Deposition	OUT 3	Leaching
IN 4	Biological N fixation	OUT 4	Gaseous losses
IN 5	Sedimentation	OUT 5	Erosion

Table 1. Factors governing nutrient flows in the soil

There is an obvious need for new research in this direction. In particular, the impact of manure, biological N fixation, crop residues, and gaseous losses.

CONCLUSIONS

New studies are necessary to improve the knowledge and cost-benefit aspects of PA,

especially concerning the environmental impact. Precision agriculture system management would increase crop production and crop profitability, decrease crop production variability, and improve soil and water quality over the present conventional uniform management. The relationships and interactions between output and input variables may represent agroecological phenomena that are both

multivariate and non-linear. This fully addresses the issues of optimal fertilization based on new Decision support systems.

The models for calculating fertilizer recommendations presented in this article can be widely used not only on the territory of Bulgaria but also in other countries, which are interested not only in obtaining the planned yields of agricultural crops but also in maintaining and increasing the soil fertility. This largely fulfills the requirement for the introduction of sustainable agricultural technology. More research and experimental work are needed to refine and create new mathematical models that take into account many factors governing nutrient flows in the soil.

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