Ecosystem vulnerability to climate change A literature review

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Abstract

This working paper reports results from a literature review on ecosystem vulnerability to climate change undertaken within the CIFOR-led project AdaptEA, funded by the Rockefeller Foundation. A total of 410 scientific publications were reviewed, with 183 studies examined in detail. The number of papers published per year increased rapidly over time, with 94 studies appearing in 2011. Of those papers with clear geographic focus, most examined European or North American ecosystems, with only 18 studies focusing on Africa. Climatic and environmental drivers considered were temperature (52% of studies), precipitation (52%), carbon dioxide (15%) and rising sea level (11%). Methods used in assessment were expert knowledge (29%), statistical inference (27%), mechanistic modelling (27%), observation (5%) and experimentation (2%). Ten per cent of studies presented concepts for vulnerability assessment. For each major assessment type, sub-types were defined and evaluated. Few approaches taken to date satisfactorily cover all relevant aspects of exposure, sensitivity and adaptive capacity of ecosystems. Climate analogue analysis is presented as an alternative approach. This method is based on a comparison of presently existing ecosystems with ecosystems at a different location, where the present climate is similar to the climate projected for the target location in the future. Potentials and limitations of climate analogues for evaluating ecosystem vulnerability are discussed.

Keywords

Climate change, ecosystems, literature review, statistical inference, species distribution modelling, mechanistic modelling, climate analogue analysis

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1. Introduction

Climate change is likely to have profound effects on both natural and man-made ecosystems. While such effects may well be beneficial in certain cases, many ecosystems are assumed to be vulnerable to climate change, in the sense that effects will be predominantly negative. Assessments of ecosystem vulnerability are crucial for identifying adaptation needs and for avoiding the worst possible consequences of climate change, for both human and natural systems. They are also needed for detecting locations and ecosystems, in which investments in adaptation and ecosystem management can produce the biggest returns.

Consequently, a large number of studies have attempted to quantify ecosystem vulnerability, in a wide range of ecological settings and using a wide range of different methodologies (e.g. Hlohowskyj et al., 1996; Strzepek et al., 1996; Hurd et al., 1999; Lassiter et al., 2000; Johnson et al., 2005). Many studies have also provided qualitative evaluations of vulnerability to climate change (e.g. Kennedy, 1995; Davidson et al., 2003; Fraser, 2006; Chapin et al., 2010; Lindner et al., 2010; Robards et al., 2011). Studies differed widely in research disciplines, geographic coverage, ecosystem type, methodological approaches, and even in authors' interpretation of the term 'vulnerability'.

The objectives of this report are to review past studies on ecosystem vulnerability, to collate and evaluate methods used in these studies and to identify efficient and effective approaches for assessing the vulnerability of natural ecosystems in Africa to climate change. Finally, this report will provide an outlook on the potential of climate analogue analysis to contribute to vulnerability analyses. Climate analogue analysis is a new approach to vulnerability assessment, which to date has not been widely used. It will find one of its first systematic applications for this purpose in the CIFOR-led AdaptEA project, for which this review was undertaken. To set the stage for this activity, the last section of the report provides an overview of the climate analogue methodology.

2. Methods

The review was based on a systematic literature search using the Scopus scientific database. This database was queried using ‘climate change ecosystem vulnerability’ as keywords, which could occur anywhere in the title, abstract or keywords of published scientific articles. Search results were supplemented by a small number of studies that we were aware of, but which were not identified by the Scopus search. Due to the restrictions imposed by the selection of keywords, this search may not have identified all studies that are relevant for the topic at hand. Nevertheless, we assume that the more than 400 papers that were found are a representative cross-section of all relevant papers. All papers were screened according to several criteria, including relevance for the present assessment, regional focus, type of methods used and inclusion of important factors related to climate change.

3. Search results

The literature search produced a total of 410 studies, published between 1994 and 2012. No article in the Scopus database that was published before 1994 contained all keywords. From that year on, there was a rapid growth in the number of articles published per year (Figure 1), up to 94 in 2011.

Figure 1. Number of articles published per year which included the keywords ‘ecosystem vulnerability climate change’ in title, abstract or keywords according to the Scopus database.

a. Relevance for the present review

Many articles were not considered particularly useful for the present study. This was the case for 55% of published studies, comprising a total of 227 articles. The proportion of articles among the total population that were closely related to ecosystem vulnerability decreased gradually over time, with 50% or more of papers published in all years before 2007 being relevant, and 50% or less in all years between 2008 and 2012 (Figure 2). This trend may reflect the increasing establishments of ‘climate change’ and ‘vulnerability’ on political and scientific agendas of many organizations. Such

establishment may lead many studies to mention the respective terms, even if the research is only marginally related to the topic.

Figure 2. Proportion of articles found by the Scopus search for ‘ecosystem vulnerability climate change’ that were considered relevant for the present assessment, and development of this proportion over time.

The number of studies that were examined in detail in this assessment was thus substantially lower than the total number of papers that the literature review identified, reaching a maximum of 27 in 2011 (Figure 3), and a total of 183.

Figure 3. Number of articles per year that were examined in detail in the present review on ecosystem vulnerability.

b. Geographic distribution

A large number of studies either had no clear geographic focus or addressed vulnerability-related issues at the global or near-global scale (Figure 4). Among continents, locations in Europe were the focus of the largest number of studies (36), closely followed by North America (33). Places in Africa were studied 18 times, and Asian locations 13 times. All other continents were represented by fewer than 10 studies.

Figure 4. Distribution of evaluated vulnerability studies across continents.

Within Africa, the focus of the research project that this review was done for, studies were evenly distributed among several countries, with a maximum of three studies focusing on any particular country (Figure 5). Among the set of studies that were reviewed, Kenya was not represented, and only one study focused on Uganda. This work (Eggermont et al., 2010) investigated historic climate impacts based on lake sediments from the Rwenzori Mountains at the border between Uganda and the Democratic Republic of Congo. This study thus did not constitute a comprehensive vulnerability assessment. To our knowledge, only the work by Claessens et al. (2007) covered some aspects of vulnerability in the Mt. Elgon region, but was limited to estimating landslide hazard. Since this study did not include a climate change angle, it was not included in this review.

Figure 5. Distribution of vulnerability studies focusing on Africa among African countries and regions.

Among all relevant studies focusing on particular ecosystems, 80% (146 studies) evaluated terrestrial ecosystems, with an additional four (2%) working on the interface between terrestrial and marine systems (Figure 6). There were also a sizeable number of papers in the latter category that were not considered relevant for the present review. These studies narrowly focused on the effects of sea level rise. Among studies on sea level rise, research that included other aspects of climate change (e.g. changes in temperature and precipitation), as well as work exploring impacts of rising sea level on non-coastal zones were retained for further review. Four per cent (4%) of papers (eight studies) investigated marine systems, 3% freshwater systems (six studies) and one study ecosystems in both environments (evaluation of marine and freshwater fisheries; Hlohowskyj et al., 1996). Eighteen (18) studies (10%) were concerned with general concepts which could not clearly be assigned to particular ecosystem types, or they investigated the vulnerability of all ecosystem types.

Figure 6. Ecosystem types evaluated among all relevant studies included in this review.

c. Climate factors

Among the studies identified as relevant for the present review, 52% included an evaluation of temperature effects (Figure 7). With only one exception, all these 96 studies also covered the effects of precipitation. The impact of elevated CO₂ concentrations was only evaluated by 15% of all studies. The effect of rising sea levels, which is only expected to affect coastal ecosystems, was evaluated by 11% of studies.

Figure 7. Inclusion of climate factors among the reviewed studies.

d. Assessment types

The different approaches that have been used to evaluate ecosystem vulnerability can broadly be grouped into five categories. The most common approach among the present set of studies is expert knowledge, in which information from various sources is assembled to gain understanding about system vulnerability. This approach was used in 29% of studies (53 in total). The second major assessment method, statistical inference, was used 50 times (27%). In this approach, environmental indicators are collected or modelled, and combined into overall vulnerability evaluations or indices. Mechanistic approaches were also used 50 times (27%). In mechanistic studies, ecosystem dynamics are represented quantitatively by models, and these models are used to estimate ecosystem responses to change. Nine (9) studies (5%) used observations for vulnerability assessments. Since the most severe climate change effects are expected in the future, however, the usefulness of this approach for assessing ecosystem vulnerability is debatable. A small number of studies (three, or 2%) used experiments to evaluate ecosystem responses. Finally, 18 studies (10%) provided concepts of vulnerability, but without concrete implementation and most often without quantitative guidance. More details on assessment types will be discussed in Section 5.

Figure 8. Assessment types used in vulnerability evaluations represented among the relevant studies.

The majority of studies (73%) evaluated system vulnerability using a forward-looking perspective and 16% based their assessments on monitoring results (Figure 9). Both approaches were combined in 8% of cases, and in 3% of articles the perspective was not clear.

Figure 9. Perspective used in vulnerability evaluations (forward-looking or monitoring).

Studies falling under the assessment types of statistical inference or mechanistic modelling normally rely on scenarios, with which future changes are anticipated. Among the 87 relevant studies in these categories, the majority (57%) relied on the outputs of Global Climate Models (GCMs) for scenario-building (Figure 10). A further 5% used Regional Climate Models (RCMs), in which GCMs were used to set boundary conditions. Eight percent (8%) of studies used arbitrary scenarios, in which climatic conditions were perturbed in a systematic manner not derived from climate models. Three percent (3%) of studies used sea level rise scenarios, while 1% of studies relied on scenarios of weather patterns (dry and wet periods) and inferred climate change impacts from these. A quarter of all studies used no recognizable scenarios for climate change analysis.

Figure 10. Percentage of statistical inference and mechanistic studies using different types of future scenarios for climate change vulnerability assessment.

Among those studies that used GCM or RCM scenarios, 19 (35%) used only one climate scenario in the analysis (Figure 11). In 47 out of 54 studies (87%), less than five scenarios were used. In five studies, 14 or more climate scenarios were applied for evaluating climate change vulnerability.

Figure 11. Number of climate scenarios used in studies based on Regional or Global Climate Models, among articles using mechanistic modelling or statistical inference for vulnerability assessment.

4. Vulnerability concepts

The array of papers that were reviewed clearly reflected an evolution in the concept of vulnerability over the past two decades. Important concepts encountered among the studies that were evaluated are reported in this section.

Early climate change vulnerability studies did not follow a universally agreed-upon definition of vulnerability. This changed with the publication of the Third Assessment Report by the Intergovernmental Panel on Climate Change (IPCC, 2001), which defined vulnerability as a combination of exposure, sensitivity and adaptive capacity. In this conceptualization, exposure is defined as “the climate change-related stress that a system experiences”, sensitivity is “the degree to which a system will respond to a given change in climate, including beneficial and harmful effects”, and adaptive capacity is “the degree to which adjustments in practices, processes, or structures can moderate or offset the potential for damage or take advantage of opportunities created by a given change in climate” (IPCC, 2001). Since the publication of the IPCC report, this vulnerability concept has increasingly been used in vulnerability assessments. Occasionally, more clarifications have been added to the approach (Turner et al., 2003; Johnston and Williamson, 2007). A few other concepts have also been proposed. With the exception of the ‘Panarchy’ framework (Section b, page 11), we do not consider frameworks presented in the assemblage of studies analyzed as full conceptual frameworks, so they will not be reported here. Many studies also follow no clear concept of vulnerability, and these articles often clearly fall short of covering all aspects identified as important in the IPCC definition.

a. The IPCC's vulnerability concept

According to the IPCC (2001), vulnerability is composed of three factors: exposure, sensitivity and adaptive capacity. Although this concept is useful, its full application is not straightforward. All three components have been interpreted in various ways:

Exposure

Exposure is mostly interpreted to mean the quantitative change in climatic parameters, such as temperature, precipitation or atmospheric carbon dioxide concentration, that systems are exposed to in a given climate scenario. However, Dawson et al. (2011) have argued that changes in habitat suitability indices, which are key components of many vulnerability assessments, should also be classified as exposure rather than containing elements of sensitivity or even being considered full vulnerability assessments in their own rights. They justify this point with the remark that changes in habitat suitability do not automatically lead to changes in species distributions, in particular for perennial species, and are thus only indicators of stresses on the systems. For such stresses, exposure appears to be the more appropriate term.

Sensitivity

Interpretations of sensitivity are more variable than for exposure. This term is most clearly defined in projections of sea-level rise impacts, where a given temperature increment is translated into increases in water levels by a seemingly linear transfer function. For more complex systems, sensitivity is often embodied in mechanistic models in the form of mathematical equations. In more statistical approaches, such as ecological niche modelling, it is often difficult to find explicit expressions of sensitivity, and some authors have integrated aspects of the IPCC's terminology by combining exposure and sensitivity into 'potential impact' (Metzger et al., 2005). System diversity has also been used to describe sensitivity, but this factor can also fall under adaptive capacity.

Adaptive capacity

Adaptive capacity (AC) is the most elusive factor of vulnerability. For human systems, this concept can include a wide range of components, such as the diversity of livelihood systems (which could also fall under sensitivity), the ability to innovate, education levels and the existence and strength of social networks. Strictly speaking it should include all factors that contribute to the ability of a community to make adaptive adjustments to the processes, practices and structures of their environment. Such adjustments are normally assumed to be conscious decisions to respond to environmental change. Attempts to define adaptive capacity for natural ecosystems have been relatively rare, and they are qualitatively different from definitions of human systems. In natural ecosystems, deliberate and directional action cannot be expected from any ecosystem component, so adaptive capacity must arise from the configuration of components that are present in the system. Thorough assessment of the adaptive capacity of a species requires detailed understanding of its life cycle, and for complex ecosystems, this knowledge must extend to all major species that are present. Measures that have been used to approximate AC are the diversity of ecosystems, the plasticity of a species, the mobility of individual organisms, including dispersal mechanisms, or the existence of climate gradients in the vicinity. Czucz et al. (2011) have added habitat connectivity vs. fragmentation as a crucial determinant of AC.

Most studies clearly fall short of providing a full assessment of vulnerability that includes all relevant factors, and all elements of the IPCC's framework can only be recognized in very few assessment.

b. The Panarchy framework

Fraser et al. (2005) present the 'Panarchy' framework, borrowed from landscape ecology (Gunderson and Holling, 2002), for evaluating the vulnerability of food systems. In this framework, vulnerability is evaluated based on wealth, connectivity and diversity of a system. In this framework, wealth is the amount of assets accumulated in a system, and high wealth equates to a high potential for losses. For example, an ecosystem with a large number of endemic species (great wealth) has more to lose than a less diverse system. Connectivity is reflective of the ability of species to adapt. Where ecosystem fragments are connected with each other, it is easier for species to adjust their ranges than where each fragment is isolated. The final component, diversity, is also an indicator of a system's ability to adapt, because diversity allows for different species to fulfill important ecosystem tasks. For being able to work on food systems, Fraser et al. (2005) adjusted the three factors to fit the different context, e.g. by interpreting 'wealth' as 'entitlements', rather than using wealth in the socioeconomic meaning of the word, where it would be a contributor to resilience rather than a factor leading to higher vulnerability. In an elaboration of this framework, Czucz et al. (2010) combine the indicators 'connectivity' and 'diversity' into a measure of the adaptive capacity of ecosystems.

5. Assessment types

a. Expert knowledge

Reviews, participatory methods and case studies

Many vulnerability assessments are derived from expert knowledge, most frequently in the form of a literature review (50 studies; Figure 12). Such evaluations have been conducted for many ecosystems, such as coastal systems (Turner et al., 1996), forests (Spittlehouse, 2005; Lasco et al., 2008), tropical alpine areas (Buytaert et al., 2011), tropical montane cloud forest (Loope and Giambelluca, 1998) and drylands (Thomas, 2008).

Other forms of expert knowledge were solicited in participatory ways using interviews, workshops and surveys. Only two studies in the present sample employed this approach. Lagos (2007) reports on an expert workshop used to define a framework for comprehensive vulnerability assessment. The actual assessment, however, is unlikely to be based on expert knowledge alone. Ogden and Innes (2007) based their assessment of forest vulnerability in Canada on a survey filled by forestry practitioners. One further study (Williams, 2000) used lessons learned from the case study of Australia's forests to infer general lessons for climate change adaptation, with particular focus on biodiversity conservation.

Figure 12. Methods employed in expert knowledge-based vulnerability assessments covered by the present review.

Expert knowledge-based assessments, in particular reviews, are useful for providing an overview of relevant factors involved in ecosystem vulnerability, but they typically do not convey much quantitative information for the specific context of a particular ecosystem. Review articles tend to collect evidence from a wide range of similar but not identical situations, and it is often unclear to what extent results are transferable. There is typically no evaluation framework, which can integrate the often somewhat disparate pieces of collected information into a comprehensive evaluation of system vulnerability. Notwithstanding these concerns, comprehensive assessments of expert knowledge provide a useful entry-point for vulnerability evaluations, and they can be instrumental for guiding more quantitative assessments of vulnerability targeting particular ecosystems in particular locations.

b. Statistical inference

Statistical inference has been the basis of 50 studies in this dataset. This approach starts with a correlation of certain indicators of ecosystem type or ecosystem function with climatic variables. In most cases, it then assumes that the statistical relationships determined in the current climate will remain valid in the future and uses these relationships for projecting climate change impacts and vulnerability.

Among the studies based on statistical inference, the majority (44%) used some sort of distribution modelling procedure (Figure 13). Sixteen (16) studies (32%) based their evaluations on multiple system vulnerability indicators, while 10% used simple statistical correlations between vulnerability

proxy variables and climate. Six studies provided little assessment of ecosystem responses, but only evaluated changes in climate, while one study focused only on reconstructing past climate vulnerability.

Figure 13. Methods applied in vulnerability assessments based on statistical inference.

Distribution modelling

The most common type of statistical inference among the surveyed studies is species distribution modelling, alternatively labelled ecological niche modelling in the literature. In this technique, modern distribution of ecosystems or species are related with climate variables, which are then used to delineate the climatic requirements of the respective ecosystem or species. These requirements are used to map potential future habitats. One example of an empirically defined climate-ecosystem relationship is the Holdridge Life Zone Classification (Holdridge, 1947), which assigns ‘plant formations’ based only on temperature, precipitation and evaporation. This system was used, for example, to project future life zone distributions for Cameroon and Ghana (Dixon et al., 1996), for Zimbabwe (Matarira and Mwamuka, 1996) and for Mexico (Villers-Ruiz and Trejo-Vazquez, 1997, 1998). In these examples, the statistical or empirical correlation of life zones and climate was provided externally, through Holdridge’s (1947) original study.

In recent years, a number of methods have arisen that establish climate-vegetation relationships based on species or ecosystem distribution data supplied to computing algorithms. A commonly applied technique to accomplish this feat is maximum entropy modelling (Phillips et al., 2006), which has been used to outline future habitats of American bullfrogs in South America (Nori et al., 2011) and parkland agroforestry systems throughout the West African Sahel (Luedeling and Neufeldt, 2012). Maximum entropy modelling was also instrumental in the production of future potential vegetation maps for East Africa (Van Breugel et al., 2011). Alternative approaches to species or ecosystem distribution modelling include data mining with classification trees, Random Forests, Genetic

Algorithms (such as GARP for distribution modelling) and other techniques. For example, Casalegno et al. (2010) used Random Forests for mapping vulnerability of *Pinus cembra* in the Alps and Carpathian mountains.

We also classified some studies that have used mechanistic models under the niche modelling category, because mechanistic models were only used to produce ecological proxies rather than for truly simulating ecosystem processes. This is true for the work of Schimel et al. (1997), who used biogeochemical indicators, derived from process-based models, for assigning future vegetation types. Similarly, a recent assessment of climate change effects on forest types in India (Chaturvedi et al., 2011) was based on model runs of the IBIS vegetation model, but none of the detailed simulation processes were adapted to site-specific conditions in the study region. The model thus provided useful indicators of vegetation type but since it did not simulate ecosystem processes, the study cannot truly be called mechanistic.

Ecological niche modelling and life zone assignment is useful for illustrating the pressures that ecosystems or species will be subjected to by future climate change. However, for most species and in particular for entire ecosystems, it is unlikely that by the projection horizons used in climate change studies, the projected distributions will actually be realized. While it is possible for organisms with very short life cycles and/or high mobility to quickly shift their distributional ranges, long-lived and mostly stationary organisms such as trees are much slower in adjusting to changes in habitat suitability. The same applies for entire ecosystems. Changes in potential habitat cannot capture the actual responses of ecosystems to climate. Consequently, they are not useful for assessing all important factors of vulnerability, mostly denying existing ecosystems any sort of adaptive capacity. Such approaches are thus useful indicators of the potential impact of climate change, but do not constitute a full vulnerability assessment. According to Dawson et al. (2011), niche models only cover one of the major constituents of vulnerability, exposure, because they do not adequately address the sensitivity of existing systems or their adaptive capacity.

Indicator-based approaches

Several studies have projected how certain environmental or socioeconomic indicators will be affected by climate change and used these changes to evaluate ecosystem vulnerability. For example, the ATEAM project (e.g. Schröter et al., 2005; Metzger and Schröter, 2006; Metzger, Schröter, et al., 2008; Rounsevell and Metzger, 2010) quantified vulnerability by proxy indicators, such as the agricultural land area, soil organic carbon content, net annual stem wood increment and net annual biomass production. Some of these indicators are derived from mechanistic modelling components, but these are based on relatively coarse-level ecological or socioeconomic processes, and they are not combined in a full mechanistic ecosystem modelling framework. Such assessments are thus able to work on large geographic scales, such as all of Europe in the ATEAM example, but they may be missing important climate change effects on particular ecosystems. A number of studies have also derived ecosystem vulnerability using large-scale biogeochemical indicators, such as net primary productivity (Moldenhauer and Lüdeke, 2002), which are assumed to approximate ecosystem dynamics. Hydrological indicators have also been used, for example in predicting habitat suitability for early life stages of salmon in British rivers (Walsh and Kilsby, 2007). Mkanda (1996) used various ecological indicators for characterizing vulnerability of nyala antelopes in Lengwe National Park in Malawi. Malone and Brenkert (2008) project vulnerability of Indian states based on a wide range of socioeconomic indicators, such as Gross Domestic Product per capita, population without access to

clean water, life expectancy or proportion of the land area that is managed. Such indicators are often combined into vulnerability indices.

Indicators used in the above-mentioned studies may be proxies of vulnerability, but the nature of the relationship between the proxies and ecosystem vulnerability is not clear. When indicators are processed into vulnerability indices, the mathematical equations used for making the index often appear arbitrary.

Many indicator-based studies do not capture all factors of vulnerability, and in particular for quantifying adaptive capacity over large areas, indicators are not always convincing. For example, Malone and Brenkert (2008) use the proportion of land that is unmanaged, the amount of sulfur dioxide emissions per unit land area and the population density as proxies of adaptive capacity (termed environmental capacity). Even vulnerability assessments that contain indicators of all components of vulnerability do not provide information on how these indicators will determine which systems are vulnerable and which ones are not. For example, Malone and Brenkert (2008) used the geometric mean of the vulnerability components for calculating a vulnerability index, but provide no justification for this choice. For most indicator-based studies, it is thus difficult to interpret results in a quantitative manner.

c. Mechanistic modelling

Mechanistic models try to capture all the important relationships in a given context and express these as mathematical equations. They thus attempt to represent all elements that contribute to a system's vulnerability in a process-based framework. Wherever such an exercise is successful, and all important processes are included, this type of assessment can allow true simulation of ecosystem dynamics, they can be run for different climate change scenarios and thus produce results that are directly linked to ecosystem vulnerability. Of the 50 studies that used this approach, our review encountered 10 that used predominantly biogeochemical models, nine that used comprehensive ecosystem models, and eight each that used hydrologic or dynamic vegetation models (Figure 14). Five studies integrated models from different disciplines. Four studies each modelled crop production and the impacts of sea level rise in mechanistic frameworks. One study provided only a conceptual model, and one study applied an agent-based modelling approach.

Figure 14. Methods applied in vulnerability assessments based on mechanistic approaches.

Sea-level rise and hydrologic models

Mechanistic models are most convincing, where systems are relatively simple. In the context of climate change, this is particularly the case for sea level rise studies, which typically consist of elevation models of coastlines, estimates of sea level increments, and sometimes the Bruun rule, which can be used to estimate coastal retreat. Such studies have been conducted for the implications of sea level rise in The Gambia (Jallow et al., 1996), Estonia (Kont et al., 1997, 2003, 2008), the United Kingdom (de la Vega-Leinert and Nicholls, 2008), Germany (Sterr, 2008), Florida (Chu-Agor et al., 2011) and Viet Nam (Boateng, 2012). Some of these studies have not only estimated coastal retreat, but also the value of assets in the affected zones. Other hydrological issues have also been modelled with fairly convincing quantitative frameworks. For example, Strzepek et al. (1996) present a water balance model for Egypt, Palmer et al. (2008) studied climate change impacts on major river basins and Weiss and Alcamo (2011) used the WaterGAP model to project future water resources across Europe. Compared to complex ecosystems, hydrological systems are relatively easy to model, because the physical properties of water are known with great certainty.

Biogeochemical models

For many biogeochemical processes, relatively widely applicable equations exist, which can be used in climate change vulnerability studies. For example, Ren et al. (2011) modelled the effects of climate change and ozone concentrations on net primary productivity (NPP) in China and Imhoff and Bounoua (2006) and Moldenhauer and Lüdeke (2002) modelled NPP globally. In particular the carbon cycle has been the subject of several recent studies (Leemans and Eickhout, 2004; Ito, 2007; Balshi et al., 2009). While biogeochemical models make it possible to study many important processes at large geographic scales, information provided by such models is of limited applicability for evaluating ecosystem vulnerability. While changes in biogeochemical parameters certainly affect

ecosystems, the effect of such changes is difficult to predict. Changes will affect currently existing ecosystems and immediate replacement of the system with one that is more aligned with the new balance of biogeochemical processes is not possible. Consequently, in the context of vulnerability assessment, these models – similarly to distribution models – do not adequately deal with sensitivity or adaptive capacity of existing systems.

Crop and dynamic vegetation models

Crop models and dynamic vegetation models stand out as the only mechanistic models encountered in this review that actually attempt to capture ecosystem or at least organism-level processes. In advanced crop models, all (or most) relevant physiological processes are contained, and relatively accurate prediction of crop yields is possible. This makes this type of models potentially suitable for climate change vulnerability assessments, at least if models have been tested over a wide range of climate conditions that includes the range of climates expected in the future. Crop models used among the studies considered as relevant were CropSyst (Tingem and Rivington, 2009; Tingem et al., 2009), InfoCrop (Aggarwal et al., 2006) and CERES-Maize (Makadho, 1996). While crop models are among the most reliable biological models available, their validity for climate change studies, in particular with regards to the effects of elevated CO₂, is under debate.

For complete ecosystems, several generalized ecosystem models are available, which have been used in vulnerability assessments. These are not actual representations of local ecosystems, but they include major ecosystem processes in a generalized manner. They can thus be used without requiring extensive data collection. The ecosystem model IBIS, for example has been used for modelling the vulnerability of Indian forests to climate change (Gopalakrishnan et al., 2011), the PICUS ecosystem model was used for forests in Austria (Lexer and Seidl, 2009; Seidl et al., 2011a, 2011b), and the LPJ-GUESS model was used to simulate vegetation dynamics on Mediterranean islands (Gritti et al., 2006), in the Sahel (Seaquist et al., 2009) and globally (Scholze et al., 2006). These models produce valuable information about ecosystem responses, but since they do not actually simulate any specifics of ecosystems, they only provide proxies of ecosystem dynamics.

More specific ecosystem models exist, for example WETSIM (Johnson et al., 2005) and WETLANDSCAPE (Johnson et al., 2010) for wetlands and SAVANNA (Christensen et al., 2004) for savannah ecosystems. Such models are more specifically attuned to the conditions of a particular habitat type and probably among the best ecological models for ecosystem vulnerability assessments. Yet these models also suffer from uncertainty about the validity of climate-ecosystem dynamics for climate change scenarios.

Integrated models

Especially for ecosystems that are strongly affected by human action or for human systems, vulnerability assessment is not meaningful without including dynamics beyond the scale of the ecosystem under study. In such cases, integrated models can be assembled, in which all major influential systems are represented. Several instances were found among the relevant studies, in which models from different disciplines were combined. For example, Antle et al. (2004) combined the CENTURY crop-ecosystem model with an econometric model, and Quinn et al. (2001) combined different modelling approaches into an integrated model to predict water, social and economic impacts of climate change on the San Joaquin Basin in California. Such models are desirable in vulnerability assessments, but require a lot of knowledge about many different aspects of the

ecosystem and beyond, and robust understanding of the climate responses of all these aspects. In most practical situations, such knowledge is not available.

Conceptual and agent-based models

One study provided a purely conceptual model of the factors leading to recent greening in some parts of the Sahel (Sendzimir et al., 2011). The authors assembled what they considered as causal relationships between very different components of Sahelian human-environment systems into conceptual diagrams. These are provided without actual information on the nature of these relationships. While the study thus does not provide a quantitative assessment of the system in question, the conceptualization and the approach used are highly valuable for understanding the complex relationships often involved in responses of ecosystems to disturbance.

One study used an agent-based modelling approach to simulate effects of climate change and policy on watersheds in the Cascade Mountains of Oregon (Nolin, 2012). This study consists of an integrated modelling framework containing many aspects of hydrologic and ecosystem dynamics, as well as an agent-based component to simulate stakeholder responses to policy scenarios. For understanding the effects of human decisions on ecosystems in a comprehensive manner, such a framework seems very valuable.

Potential shortcomings of mechanistic models

Ecosystems are complex, and capturing all the important dynamics that ultimately determine system vulnerability is very challenging. When the threat of climate change is reduced to the impacts of sea-level rise, this process seems quite manageable. When climate change impact modelling requires detailed knowledge of climate responses of many organisms, this exercise becomes very difficult, in particular when interactions between species are also to be modelled. Consequently, ecosystem models either come across as simplistic, when only a few environmental factors are modelled, or they are so complex that they are difficult to understand. Where models become very complex, it is also worth considering that every additional equation that enters a model introduces additional uncertainty. Results from very complex models can thus become extremely uncertain, and ultimately provide little concrete information. In such cases, a purely conceptual model (e.g. Sendzimir et al., 2011) may convey all the relevant information, without making quantitative projections on a very narrow base.

In fact, in mechanistic models of ecological systems, the accuracy of modelled relationships is a substantial challenge. Accurately determining, e.g., the temperature responses of a given organisms requires experimentation under controlled conditions. It may be realistic to accomplish this for insects in the context of a vulnerability study, but certainly not for mature trees. For accurately determining how effectively various organisms compete for certain resources in an ecological system, much more complex experiments or very detailed field studies are needed. A particular problem arises from the fact that models developed for climate change analysis must be valid for use under environmental conditions that are outside the climatic domain, in which observations can inform model development. In other words, a model developed from observations in currently existing ecosystems must be valid for a slightly warmer and potentially dryer or wetter environment than what is observable today. Almost by definition, most models will not be valid for such extrapolation, and we often cannot be confident that ecological relationships determined in the field will remain valid under new climate conditions. Box 1 provides an example of this.

Box 1. Winter chill models for climate change projection

For temperate fruit trees, available winter chill is an important determinant of a location's suitability for a particular tree cultivar. Winter chill is needed for signaling to the tree that the winter is over and that dormancy can be broken without incurring a high risk of frost damage to new growing tissue. Several models exist for quantifying winter chill, and many of them have been used for climate change projections (Luedeling, 2012). The existence of more than one model provides an opportunity to illustrate the effects that inaccurate models can have in climate change projection.

Figure 15. Winter chill distribution for a location in California for a 1950s scenario (left; consisting of 100 simulated years of weather) and for a particular 2050s climate scenario (right), quantified with four commonly used models (Chilling Hours, Utah Model, Positive Utah Model, Dynamic Model). The divergence between the different models in the 2050s scenario indicates that the choice of the model is the primary determinant of identified change (Luedeling et al., 2009)

Figure 15 shows winter chill projected with four different models for the same location and the same climate, relative to a baseline climate (Luedeling et al., 2009). Were models equivalent, the distributions should be looking identical for all models. This is clearly not the case, with substantial quantitative differences between projections. In this particular example, the issue can be explored further, models can be compared, and the most accurate model used for further work. For many ecological processes, however, only one model is available or widely used and its accuracy is often not known. As illustrated in the figure, the mathematical layout of the model can have an enormous impact on quantitative model results. Where these effects cannot be quantified, it is very difficult to evaluate model accuracy, especially if many such models are combined into a larger modelling framework.

d. Monitoring and observation

Nine vulnerability assessments have focused on evaluation of observed ecosystem indicators. Such studies have been based either on observations from the past or on snapshots of the present. Among these studies, it is difficult to generalize, because the methodologies that were used have little in common. For example, Lin et al. (2011) monitored the vulnerability of Taiwanese forests to tropical storms by observing damage from past storm events, and a similar approach was used to assess farm vulnerability to hurricane damage in Mexico (Alayon-Gamboa and Ku-Vera, 2011). If indicators are selected carefully, they can effectively be used to identify major sources of vulnerability. The concept

of the vulnerability cube (Fraser, 2007) allows illustrating vulnerability as a function of three indicators, representing institutional capacity, robustness of food production systems and availability of alternative livelihood options. This system is useful for identifying the most important sources of vulnerability and for developing strategies to alleviate this vulnerability (Lin and Morefield, 2011). The major disadvantage of monitoring-based vulnerability assessments is that they do not offer quantitative projections of climate change. They are relatively well suited for evaluating the adaptive capacity of systems, but they have little to offer on exposure and sensitivity. Given that historic climate change is assumed to have been relatively small compared to likely changes over the next century, it seems important to include quantitative projections of climate change impacts. Such projections can naturally not be included in an assessment based on observations alone.

e. Experiments

Arguably, the only way in which ecosystem responses can be assessed with high confidence in the results, is by experimentation, yet this approach was only taken in three vulnerability studies. Pyke and Marty (2005) present results from a grazing exclosure study in an investigation of the interactions between grazing and climate change. However, in this case the parameter that was manipulated in the experiment was not climate, but grazing intensity. Cartwright et al.'s assessment (2006) also does not manipulate climate. Among the studies reviewed, only Ripullone et al. (2009) manipulated climatic factors by partially excluding rainfall from a Mediterranean macchia ecosystem.

Experimental manipulation is difficult and costly and thus not often done. Where it is practised, the focus of the study is generally on explicitly determining climate change impacts rather than on fully evaluating system vulnerability. Many environmental manipulation studies were thus not found in this assessment. Wherever manipulation is done, the extent to which replication is possible and to which complex ecosystem dynamics can be enclosed in a manipulated environment is limited by high costs for set-up and maintenance of the system. Consequently, only small fragments of ecosystems are typically included in experiment-based vulnerability assessments.

6. Synthesis

A lot of different approaches have been taken in studies concerned with ecosystem vulnerability. Not all articles summarized in this report had the ambition to provide a comprehensive vulnerability assessment, yet all covered aspects related to this quest. It thus makes sense to summarize, based on findings presented in these papers, the adequacy of the array of methods presented for assessing ecosystem vulnerability to climate change.

Most methodologies clearly fall short of addressing all the important contributing factors to vulnerability, according to the IPCC's definition. With regard to this definition, different methodologies have different strengths and weaknesses, and a combination of different approaches may be needed to arrive at a comprehensive evaluation of vulnerability. There appears to be a trade-off between coverage of all vulnerability aspects and the provision of a quantitative evaluation. In an expert knowledge approach, it is possible to summarize all (or most) relevant factors related to exposure, sensitivity and adaptive capacity of ecosystems to climate change, but there was no study that convincingly combined all these factors into a quantitative framework. In particular adaptive

capacity, and for most species also sensitivity, normally remain speculative, because relevant processes cannot readily be observed in the field. Gaining definitive understanding of these factors requires exposing ecosystems to altered environmental conditions, which is generally not feasible for entire ecosystems. Experiments to this effect have occasionally happened, though few were included in the article sample analyzed here. The climate change impacts literature has a lot more to say on this topic. However, in the majority (if not all) of these studies, ecosystems are exposed to climatic conditions expected relatively far in the future, rather than to the gradually changing conditions that would seem more plausible. They thus represent studies of ecosystem responses to climatic shocks. Sensitivity to such shocks is likely to be quite different from sensitivity to gradual change. Adaptive capacity is even more difficult to evaluate by such experiments, because many processes related to the capacity of an ecosystem to adapt are likely to be much more effective when changes occur slowly than when systems are shocked. In-migration of new species, emergence of adapted ecotypes of species currently present, or genetic selection for tolerance to higher temperature may take many generations, which cannot be represented easily in experiments. The only way to overcome such constraints could be by observing ecosystem responses in real time, but the value of such a strategy for anticipative climate change adaptation planning would surely be limited. There may thus be a natural limitation to the accuracy, with which we can understand sensitivity or adaptive capacity of ecosystems. Modelling can of course attempt to project ecosystem responses, but unless ecosystems are quite simple, the accuracy with which we can project climate change impacts on ecosystems is probably pretty low. The following is an evaluation of how well different methodologies cover the three components of vulnerability.

a. Exposure

Exposure seems like the easiest factor to assess, yet even here definitions and approaches vary widely. Probably the simplest interpretation of exposure in the context of climate change is to summarize changes in climate that are expected. This approach was taken by several studies, including for instance work by Lal et al. (2002), who summarized expected climate change for small island states. There are good reasons for broadening the notion of exposure in the context of ecosystem vulnerability, because the concept should include exposure to climatic stress. Certain climatic changes may cause such stress, whereas changes that are qualitatively or quantitatively different leave ecosystems relatively unaffected. For quantifying stress, measures of habitat suitability or indicators of ecological performance (e.g. net primary productivity, as modelled with a Dynamic Vegetation Model) may be better indicators than changes in climate alone. This idea makes distribution models, biogeochemical models or dynamic vegetation models (when not parameterized to site-specific ecosystems) appear like the best available tools for assessing exposure. It seems fairly clear that, though often claimed, the mentioned modelling approaches cannot capture more aspects of ecosystem vulnerability beyond exposure, because they do not provide information on how existing systems respond to changes in environmental stress levels.

b. Sensitivity

For assessing sensitivity, only models that are specific to the system in question are useful. Such models must capture the climate sensitivity of all, or at least the most important, components of the systems, and instill confidence that interactions between components are represented sufficiently

accurately for predicting ecological outcomes at the system level. For some simple systems, models that convincingly represent important factors exist, most notably for the relatively simple hydrologic studies on land lost due to sea level rise and changes in water cycles due to climate change. For well parameterized agricultural crop models, confidence in the accuracy, with which climate sensitivity is captured, is also relatively high, even though many open questions still surround CO₂ effects on plant growth. Given substantial interest in this topic, current research efforts and some past modelling successes, it can be expected that reliable crop models will be available for wider use fairly soon. For ecosystems that consist of more than one species, however, making reliable models is much more challenging. Such ecosystems contain a lot of different organisms, each with its own sensitivity to climate change. In addition to individual responses, climate change is likely to affect interspecific competition and change the ecological balance of systems. So while some ecosystem models are available for modelling complex situations, confidence in the outputs should be substantially lower than for models targeting individual species or abiotic processes.

c. Adaptive capacity

Adaptive capacity of natural ecosystems is a challenging concept. This factor is already difficult to address for human communities, where many factors that have been identified as contributors to adaptive capacity are not easy to assess, in particular when a quantitative estimate is the goal. This is true for the ability of a community to innovate, for the strength of social networks and other similar factors. Metrics have been developed for quantifying these factors, but it remains unclear how to best integrate them into a quantitative vulnerability framework. For natural ecosystems, the notion is even more unclear. Ideas that have been put forward are the availability of potentially better adapted ecosystems in close proximity and the genetic and functional diversity of existing systems, but convincing frameworks to summarize the effects of these qualities on vulnerability are – to our knowledge – unavailable.

d. Ecosystem vulnerability

Due to somewhat inadequate coverage of all factors that contribute to vulnerability, with the possible exception of exposure, evaluating ecosystem vulnerability is very difficult, and fully convincing methodologies do not exist. In contrast to human systems, it is even unclear what exactly vulnerability of an ecosystem entails. Evaluations of human systems are naturally set in the normative frame of human well-being. The perspective that is assumed is thus the perspective of the principal actors within the system under study. Indicators such as household incomes, prevalence of hunger, etc. lend themselves as indicative variables in such assessments. For ecosystems, indicators are much less apparent and there is no obvious set of norms and values inherent in the target systems, with which ecosystems can be evaluated. Provision of ecosystem services is sometimes used as a substitute, but the recipient of these services is of course not the ecosystem itself, but human society, often external to the ecosystem, according to whose perspective vulnerability is thus assessed. It is of course possible to assume that it is ‘desirable’ for ecosystems to persist in unaltered form. However, given historic changes in ecosystem composition and the likelihood that different but functioning ecosystems would establish even where certain species assemblages disappear, a vulnerability definition based on preserving the status quo seems questionable. This context raises the question, how broadly the term ‘adaptive capacity’ should be interpreted. Is the possibility that invasive species

can take over an ecosystem a symptom of vulnerability – or an indicator of adaptive capacity? Of course, this is typically interpreted as a problem, but such take-overs ensure that many ecosystem functions are maintained even as ecosystem composition changes. In the context of human societies, this could be considered equivalent to, say, a farming community switching to a pastoral lifestyle or radically changing the array of crops that are cultivated. Most human vulnerability researchers would probably consider the latter an element of adaptive capacity, whereas few ecologists would list intrusion of invasive species under this label.

The above discussion may be mostly academic in nature, but it seems worth noting that studies on vulnerability make little sense without a value system to guide the analysis. In the context of ecosystem vulnerability studies, this value system is likely to be that of the analyst, the human researcher. Ecosystem services are thus generally at the core of the assessment, focusing on carbon stocks, biodiversity, hydrological services, food and fiber production, and in some cases cultural and recreational values of ecosystems. For some of these services useful indicators can easily be defined and some of them can be modelled with some certainty. Such modelling will however always be subject to some uncertainty, because the exact quantity of a given ecosystem service that will be supplied will depend on ecosystem dynamics in the specific ecosystem under study, which normally cannot be projected in detail.

7. Climate analogue analysis for vulnerability assessment

The remaining section of this report will explore the usefulness of climate analogue analysis for ecosystem vulnerability assessment. In some respects, this method provides a ‘work-around’ solution to the uncertainties inherent in projection-based vulnerability evaluations, because it attempts to anticipate likely changes in ecosystem structure and functions based on analysis of presently existing ecosystems. These ecosystems are to be found at a location that currently has the climate that is projected for the study location in the future. The analysis method is outlined and some applications described. Finally, some limitations of the climate analogue approach are discussed.

a. Method description

The greatest challenge in assessing the vulnerability of a given ecosystem to climate change is the fact that climate change effects that are expected in the future cannot be observed today, and for most ecosystems experimental manipulation is not feasible. Most mechanistic vulnerability assessments therefore rely on process-based models, whose validity for projected future climatic conditions is unproven. As shown by the example in Box 1, even models that are widely used can be subject to substantial errors, when used outside the climatic domain they have been calibrated for. For complex ecosystems, which are shaped by many ecological interactions, prediction of what kind of ecological balances will establish under altered conditions is normally not possible, at least with a reasonable level of confidence.

Climate analogue analysis has developed as a work-around for this problem. This technique is based on the premise that for most locations, climates that are projected for the future can already be

observed today – but in another location (Luedeling and Neufeldt, 2012). At such climate analogue locations, the current climate is similar to conditions projected by certain climate models at the target site in the future (Figure 16).

Figure 16. Comparison of mean monthly rainfall, minimum temperature and maximum temperature between conditions projected for a location in Kenya (2.04°S, 37.04°E; red curves) for the 2080s (according to the CCCMA climate model and the A2a greenhouse gas emissions scenario), with current conditions at its closest climate analogue site (in this case at 2.21°S, 36.38°E; blue curves). Conditions are not identical, but probably similar enough to produce some insights about possible climate change impacts on the target site (Luedeling, unpublished).

For each available climate projection, such analogue locations can be determined, resulting in a population of sites that represent the array of future climates that climate models project (Figure 17). Evidently, the match between the projected climate at the target sites and the current climate at the best analogue location is not always very good. Especially for so-called ‘novel climates’, good analogue locations cannot be found (Williams and Jackson, 2007; Williams et al., 2007). Notwithstanding this constraint, this approach should produce reasonable climate analogues for most locations.

Figure 17. Climate analogues of a target site in Kenya (black dot) according to 18 climate change projections (colored dots; projections listed in the legend). The population of the colored dots represents the full array of climates that, according to these particular climate projections, can plausibly be expected at the target site (Luedeling, unpublished).

While climate analogues have not yet been used for vulnerability assessments in the published literature, they may have potential for contributing to such analyses. For example, their evaluation allows relatively simple appraisal of the general direction, in which certain ecosystems are headed. This can be evaluated by comparing environmental conditions between target and analogue sites. Technically, this can be achieved by sampling environmental data layers at target and a population of analogue sites and comparing ecological indicators between the locations. For example, potential crop yield layers promise to convey information about the potential for agriculture at a given site (Figure 18).

Target and analogue sites

Grid: Potential yield of rainfed maize
Site: Mau_and_Western_System_7

Figure 18. Comparison of yield potentials for rainfed maize for a baseline and 18 future climate scenarios for a location in Western Kenya, based on climate analogue analysis. Red dots indicate yield potentials at the baseline and analogue locations. The boxplot for the baseline scenario indicates the potential yield distribution among the 50 closest pixels of the climate grids to the target location, whereas for future climate scenarios, boxplots are the distributions among the 50 closest analogues, according to the 'climatic distance' measure used in the analogue identification process (Luedeling, unpublished).

Results from such analyses can be summarized into indices of environmental indicators, which provide a proxy measure of likely effects of climate change on ecosystems. Such summaries can be presented across climate scenarios for a particular location (Figure 19), or they can be mapped spatially (Figure 20).

Production vulnerability to climate change

Figure 19. Agricultural production vulnerability to climate change for a location in Kenya, based on yield potentials for the five most promising crops, extracted for target site and climate analogue locations from gridded datasets. In the figure, 'resilient' corresponds to unchanged yield potential (on average over five crops), 'highly vulnerable' indicates a decrease in yield potentials by 50% or more, and 'improving' means an increase in yield potentials by 50% or more (Luedeling, unpublished).

Figure 20. Vulnerability of agricultural ecosystems across Kenya, based on yield potentials at climate analogue locations. The color scheme is the same as in **Figure 19**, with red indicating strongly deteriorating conditions, and light green signifying significant improvements (Luedeling, unpublished).

Climate analogues may have some potential for vulnerability assessments, even for natural ecosystems. They can fairly efficiently assemble sets of multiple indicators, along the lines of methods used in studies based on the statistical inference approach. Indicators such as net primary productivity or elements of the carbon balance then have to be computed only once, for the baseline scenario, and the resulting data layers can then simply be sampled, without requiring additional model runs to produce indicators. For such a process, indicators should ideally be based on climate alone, rather than include too many site-specific characteristics which may make analogue sites not comparable with the target location. Alternatively, additional environmental or socioeconomic indicators could be included in an analogue search procedure. In such an approach, it would also be possible to enrich the mapping domain with hypothetical locations which could fill the gaps in the currently existing array of climates that will be filled by novel climates in the future.

Additional potential exists in comparing ecosystems between target and analogue locations, based on field survey. In this process, it will be important to select site pairs that do not differ so strongly in

non-climatic factors that inter-site comparisons become meaningless. Once suitable site pairs are identified, ecosystem composition and ecosystem service provision can be compared. Where ecosystems are similar between target and analogue sites, including largely similar species composition, species abundance, species ecotypes and biodiversity, it is probably safe to assume that ecosystem functioning is not at particular risk from climate change. Where these factors differ slightly, the comparison can provide insights into the ecosystem succession processes likely caused by projected climate change. This can be particularly insightful, if a series of climate analogues, representing different stages of projected climate change, can be identified and compared. If suitable analogue sites along such a future climate transect can be identified, relatively robust information on the sensitivity of ecosystems can be derived, complementing the exposure estimates produced by assembling general environmental indicators.

For human systems, climate analogues can provide insights into what kinds of adaptation measures are appropriate by collecting information about climatically adapted management at analogue sites. Land use strategies there may be candidate adaptation options for the target sites, provided that they are culturally and socially acceptable and attuned to site-specific but non-climatic environmental factors.

b. Method potential for vulnerability assessment

Climate analogues can help provide insights into both exposure and sensitivity to climate change, and they can provide valuable information for adaptation planning. Comparison between target and analogue site pairs can provide insights into the kind of changes that would have to happen in target ecosystems in order to ensure their functioning in a climatically altered future. Such comparisons can provide actionable information for assisted adaptation of natural or managed ecosystems. For example in forestry, species growing well at analogue locations may be better candidates for replanting of logged-over areas than species that were recently cut there. In planning the adaptation of national parks or conservation areas, climate analogues can also be useful, because they identify areas, from which future adapted genetic material can be sourced. Species can then either be directly transferred at an appropriate point in time, or conservation managers can work towards establishing connectivity between mostly intact ecosystems at climate analogue locations and the natural ecosystem that is to be adapted. In many geographic settings, especially in mountainous areas, climate analogue locations are likely to be close enough for the latter strategy to be feasible.

Exposure

For evaluating exposure to climate change, climate analogue analysis can probably not do more than methods applied in previous publications, but it can make their use more efficient. For example, it seems feasible to assemble exposure indicator data produced by multiple biogeochemical, hydrologic and other models and access these through a climate analogue procedure. This will require only a one-time data collation effort, the results of which could then be widely used in exposure studies for diverse ecosystems. Currently, the array of methods used in the literature is limited to the data processing capacity and technical expertise of the group doing the study, leading to a very limited selection of exposure indicators in any given study. If adequate datasets are assembled, this array can substantially be expanded to allow more users to include more indicators in their assessments, even without requiring extensive training in the use of biogeochemical and ecological models.

Sensitivity

The greatest potential of climate analogue analysis probably resides in its use for climate sensitivity assessment, for which methods currently in use are clearly suboptimal. The reason for current limitations is mainly that models on the response of ecosystems to climate change can only be developed using observations under current climate, making the validity of resulting models for future climates questionable. To a certain extent, climate analogues allow ‘collection of data in the future’. For those ecological processes that occur at both target and analogue sites, the climatic range, for which ecological models are valid, can thus be extended to include the full range of plausible climates. In contrast to the exposure analysis, sensitivity assessments will then require substantial fieldwork, a multiple of traditional approaches which only focused on one location, but the greater reliability of resulting models for future projections may be worth the extra effort.

Adaptive capacity

Obtaining hard quantitative data on adaptive capacity is difficult, even if ideal climate analogue locations can be identified. Yet comparison of ecosystem structure, genetic composition and other ecological parameters between target and analogue sites provide an indication of the changes needed to ensure future functioning of an ecosystem. Whether or not these changes are likely to happen given current ecosystem composition at the target site will probably have to be assessed through expert opinion, but climate analogues should be able to provide useful information for guiding such assessment.

c. Method limitations

Climate analogue analysis is not yet well established and many open questions currently remain. For example, it is unclear how much of the difference between ecosystems is explained by climate, compared to other environmental and socioeconomic factors, such as soil, accessibility, population density, etc. Strategies to overcome this major constraint, mainly through inclusion of relevant factors into the search for analogues, are under development but have not progressed very far. Availability of climate data is also a constraint, but increasing efforts in downscaling and improved accessibility of climate projections is working towards overcoming this obstacle. Recently, an online tool for identifying climate analogues has been published by the CGIAR Research Programme on Climate Change, Agriculture and Food Security (CCAFS; <http://gismap.ciat.cgiar.org/analogues>), which makes the method widely accessible, thus contributing to overcoming the climate data constraint. Probably the greatest constraint in using climate analogues, even where these are perfect matches of projected climate at the target location, is that projected changes in atmospheric carbon dioxide concentrations will of course not be realized at climate analogue locations. These concentrations are very homogeneous around the globe, and future projected concentrations, in particular those expected by the end of the 21st century cannot be found anywhere today. The extension of model validity domains and the realism with which ecosystem-relevant climate factors are represented at analogue locations is thus limited to rainfall and temperature.

Conclusion

Assessing ecosystem vulnerability to climate change is a challenging task, due to the difficulty in anticipating responses of systems to conditions that cannot presently be observed. Even where adequate models have been developed for particular ecosystems, these have normally been calibrated with past observations, and there is no guarantee that the established relationships will remain valid in the future. For most ecosystems, even responses to past and present climate have not been well studied and modelled, making quantitative vulnerability evaluation difficult. Thus, mechanistic vulnerability assessments reviewed in this report are mostly limited to relatively simple cases, such as coastline retreat due to sea-level rise, hydrologic responses to rainfall change or shifts in climax vegetation (as opposed to actual vegetation). Mechanistic models for particular ecosystems are very rare, and in most cases it seems unlikely that all relevant climate responses in complex ecosystems are adequately covered. This is particularly true for forest ecosystems, in which many organisms will experience shifting climates throughout their lifetimes. It is clear that no climax vegetation type can quickly be replaced by another type of climax vegetation, but we did not find successful attempts at modelling climate change-induced succession in forest ecosystems.

Statistical inference methods have been widely used, but are of limited usefulness for judging vulnerability to climate change. Most of these methods are based on associating particular ecosystems with a certain type of climate. Where climate change indicates a shift in the vegetation associated with a given location, the local ecosystem is taken to be vulnerable. This approach has a number of important limitations: it assumes that the current ecological niche fully describes the suitable area for an ecosystem, but experiences with invasive species show that many organisms thrive outside of their native climate ranges. It assumes further that ecosystems can easily replace each other, which is not generally the case. In cases where ecosystem classes are assigned to a place with a particular climate, statistical inference is very sensitive to the classification thresholds used to determine ecological zones. When using broad eco-regions, ecosystem shifts are much less likely than when using a fine-grained distinction between systems. While such statistical methods provide some indication of the direction that particular ecosystems are headed in, they fall short of being full vulnerability assessments.

Anticipating impacts of climate change on ecosystems, with the partial exception of some simple agricultural systems, remains a big challenge, but it is required for quantitatively assessing the vulnerability of ecosystems. Climate analogues offer an opportunity to glimpse some limited insights into a climatically perturbed future. At climate analogue locations, a manifestation of the projected future for a given location can be visited and investigated. If ecosystems at these locations are vastly different from those at the target location, and if these differences do not stem from obvious non-climatic differences between the sites (e.g. in soils, land use or socioeconomic conditions), the target location is likely vulnerable to climate change. An evaluation of climate analogues for multiple climate scenarios allows an appraisal of the potential impacts of a range of future climate scenarios, which can be a useful starting point for a vulnerability assessment. Climate analogues are also useful for validating the projections of mechanistic ecosystem models. If projected impacts of climate change bear no resemblance to processes currently underway at a location with a climate similar to conditions used in an impact simulation, the simulation may have weaknesses. Finally, climate analogues can be used to improve the validity of empirical models of climate change impacts. Ecosystem models developed only at a particular target location suffer the weakness that no data

corresponding to projected future conditions was used in model development. At climate analogues, such data can be collected, substantially enhancing the credibility of both statistical and mechanistic approaches to vulnerability assessment.

Nonetheless, the climate analogue approach leaves several questions unanswered. Similar to most statistical approaches, it does not allow modelling the succession of ecosystems in a changing climate, but merely provides a glimpse at a potential future ecosystem. There is also a host of site factors that may make potential climate analogue locations poor learning locations for adaptation or vulnerability assessment. Ecological setting, human activity or connectivity with similar ecosystems elsewhere are examples of factors that may constrain the usefulness of an analogue location. Identifying places where all the important conditions are met may sometimes be difficult, shedding doubt on the general applicability of the method in varied circumstances. The climate analogue approach requires more exploration to evaluate its suitability for adaptation planning and vulnerability assessment.

Appendix – List of relevant studies

Climate zones: Cold = Boreal, Arctic and Antarctic; Trop = Tropical; Temp = Temperate; Subt = Subtropical. Ecosystem type: all/no = all ecosystems or no specific ecosystem; Terr = Terrestrial; Mar = Marine; Fresh = Freshwater. Approach: Conc = Conceptual; ExKnow = Expert knowledge; StatInf = Statistical inference; Mech = Mechanistic; Experi = Experiment.

Year	Author	Climate zone	Discipline	Continent	Country	Ecosystem type	Approach	Method
1994	Epstein (1994)	Generic	Medicine	Any or global	Generic	All/no	Conc	
1995	Kennedy (1995)	Cold	Ecology	Antarctica	Antarctica	Terr	ExKnow	Review
1996	Dixon et al. (1996)	Trop	Forestry	Africa	Cameroon and Ghana	Terr	StatInf	Distribution modelling
1996	Hlohowskyj et al. (1996)	Trop	Marine	Africa	Africa	Fresh/Mar	ExKnow	Review
1996	Jallow et al. (1996)	Trop	Hydrology	Africa	The Gambia	Mar/Terr	Mech	Sea level rise model
1996	Makadho (1996)	Trop	Agriculture	Africa	Zimbabwe	Terr	Mech	Crop model
1996	Matarira and Mwamuka (1996)	Trop	Forestry	Africa	Zimbabwe	Terr	StatInf	Distribution modelling
1996	Mkanda (1996)	Trop	Ecology	Africa	Malawi	Terr	StatInf	Multi-indicator assessment
1996	Strzepek et al. (1996)	Trop	Hydrology	Africa	Egypt	Fresh	Mech	Hydrologic model
1996	Turner et al. (1996)	Generic	Hydrology	Any or global	Generic	Mar/Terr	ExKnow	Review
1996	Warrick et al. (1996)	Generic	Ecology	Multiple	New Zealand and Bangladesh	Terr	Mech	Integrated model
1997	Kont et al. (1997)	Temp	Hydrology	Europe	Estonia	Mar/Terr	Mech	Sea level rise model
1997	Schimel et al. (1997)	Temp	Ecology	North America	USA	Terr	Mech	Biogeochemical model
1997	Villers-Ruiz and Trejo-Vazquez (1997)	Subt/Trop	Forestry	Central America	Mexico	Terr	StatInf	Distribution modelling
1998	Benzing (1998)	Trop	Ecology	Any or global	Generic	Terr	ExKnow	Review
1998	Hutjes et al. (1998)	Generic	Hydrology	Any or global	Generic	All/no	ExKnow	Review
1998	Loope and Giambelluca (1998)	Trop	Ecology	North America	USA	Terr	ExKnow	Review

Year	Author	Climate zone	Discipline	Continent	Country	Ecosystem type	Approach	Method
1998	McMichael et al. (1998)	Generic	Medicine	Any or global	Generic	Terr	ExKnow	Review
1998	Villers-Ruiz and Trejo-Vazquez (1998)	Trop	Forestry	Central America	Mexico	Terr	StatInf	Distribution modelling
1999	Hurd et al. (1999)	Generic	Hydrology	Any or global	Generic	Terr	StatInf	Multi-indicator assessment
1999	Rötter and van de Geijn (1999)	Generic	Ecology	Any or global	Generic	Terr	ExKnow	Review
1999	Shafer (1999)	Generic	Agriculture	Any or global	Many	Terr	ExKnow	Review
2000	Ayres and Lombardero (2000)	Generic	Multi-disciplinary	North America	Canada/USA	Terr	ExKnow	Review
2000	Fairbanks and Benn (2000)	Subt	Ecology	Africa	South Africa	Terr	Obs	
2000	Fisher (2000)	Generic	Multi-disciplinary	North America	USA	All/no	ExKnow	Review
2000	Kittel et al. (2000)	Cold	Ecology	Arctic	Arctic	Terr	ExKnow	Review
2000	Lassiter et al. (2000)	Temp	Ecology	North America	USA	Terr	StatInf	Distribution modelling
2000	Miles et al. (2000)	Temp	Hydrology	North America	USA	Fresh	Mech	Hydrologic model
2000	Williams (2000)	Temp	Ecology	Australia	Australia	Terr	ExKnow	Case studies
2000	Wollmuth and Eheart (2000)	Temp	Hydrology	North America	USA	Terr	Mech	Hydrologic model
2001	Jungo and Beniston (2001)	Cold	Meteorology	Europe	Switzerland	Terr	StatInf	Climate statistics
2001	Krol et al. (2001)	Trop	Multi-disciplinary	South America	Brazil	Terr	Mech	Integrated model
2001	Quinn et al. (2001)	Cold	GIS and modelling	North America	USA	Terr	Mech	Integrated model
2002	Haboudane et al. (2002)	Subt	Biogeochemistry	Europe	Spain	Terr	Mech	Biogeochemical model
2002	Lal et al. (2002)	Generic	Climate change modelling	Any or global	Many	Mar/Terr	StatInf	Climate statistics
2002	Moldenhauer and Ludeke (2002)	Generic	Ecology	Any or global	Global	Terr	Mech	Biogeochemical model
2002	Scott et al. (2002)	Temp	Ecology	North America	Canada	Terr	StatInf	Distribution modelling
2002	Tol (2002)	Global	Economics	Any or global	Many	Terr	StatInf	Statistical correlations
2003	Davidson et al. (2003)	Temp	Multi-disciplinary	North America	Canada	Terr	ExKnow	Review
2003	Dulvy et al. (2003)	Global	Ecology	Any or global	Global	Mar	ExKnow	Review

Year	Author	Climate zone	Discipline	Continent	Country	Ecosystem type	Approach	Method
2003	Kont et al. (2003)	Temp	Ecology	Europe	Estonia	Terr	Mech	Sea level rise model
2003	Leathwick et al. (2003)	Temp	Ecology	Australia	New Zealand	Terr	StatInf	Distribution modelling
2003	Parson et al. (2003)	Temp	Multi-disciplinary	North America	USA	All/no	ExKnow	Review
2003	Turner et al. (2003)	Generic	Ecology	Any or global	Any	All/no	Conc	
2004	Antle et al. (2004)	Cold	Economics	North America	USA	Terr	Mech	Integrated model
2004	Christensen et al. (2004)	Subt	Ecology	Asia	China	Terr	Mech	Ecosystem model
2004	Danis et al. (2004)	Cold	Hydrology	Europe	France and Germany	Fresh	Mech	Hydrologic model
2004	Diodato (2004)	Cold	Hydrology	Europe	Italy	Fresh	StatInf	Climate statistics
2004	Forbes et al. (2004)	Cold	Multi-disciplinary	Arctic	Arctic	Terr	ExKnow	Review
2004	Leemans and Eickhout (2004)	Global	Climate change modelling	Any or global	Global	Terr	Mech	Biogeochemical model
2004	Lewsey et al. (2004)	Trop	Marine	Central America	Caribbean	Mar	ExKnow	Review
2004	Messerli et al. (2004)	Global	Hydrology	Any or global	Global	Terr	ExKnow	Review
2004	Sutherst (2004)	Generic	Medicine	Any or global		All/no	ExKnow	Review
2005	Easterling and Apps (2005)	Generic	Ecology	Any or global	Generic	Terr	ExKnow	Review
2005	Fraser et al. (2005)	Generic	Ecology	Any or global	Generic	Terr	Conc	
2005	Hulme (2005)	Generic	Ecology	Any or global	Many	Terr	ExKnow	Review
2005	Johnson et al. (2005)	Cold/Temp	Ecohydrology	North America	Canada/USA	Terr	Mech	Ecosystem model
2005	Krysanova et al. (2005)	Temp	Ecohydrology	Europe	Germany	Terr	Mech	Hydrologic model
2005	Metzger et al. (2005)	Generic	GIS and modelling	Europe	Europe	Terr	StatInf	Multi-indicator assessment
2005	Perarnaud et al. (2005)	Generic	Meteorology	Any or global	Generic	Terr	ExKnow	Review
2005	Pyke and Marty (2005)	Subt	Ecology	North America	USA	Terr	Experi	Experiment
2005	Rounsevell et al. (2005)	Temp/Subt	GIS and modelling	Europe	Europe	Terr	StatInf	Distribution modelling
2005	Schröter et al. (2005)	Temp/Subt	GIS and modelling	Europe	Europe	Terr	StatInf	Multi-indicator assessment
2005	Spittlehouse (2005)	Cold/Temp	Forestry	North America	Canada	Terr	ExKnow	Review
2006	Aggarwal et al. (2006)	Trop	Agriculture	Asia	India	Terr	Mech	Crop model

Year	Author	Climate zone	Discipline	Continent	Country	Ecosystem type	Approach	Method
2006	Bakkenes et al. (2006)	Temp	Multi-disciplinary	Europe	Europe	Terr	StatInf	Distribution modelling
2006	Cartwright et al. (2006)	Temp	Marine	Europe	UK	Terr	Experi	Experiment
2006	Chapin et al. (2006)	Cold	Ecology	North America	USA	Terr	ExKnow	Review
2006	Coulson and Joyce (2006)	Generic	Ecology	Any or global		Terr	StatInf	Climate statistics
2006	Folke (2006)	Generic	Sociology	Any or global	Many	Terr	ExKnow	Review
2006	Fraser (2006)	Global	Sociology	Any or global	Global	Terr	ExKnow	Review
2006	Gritti et al. (2006)	Subt	Biogeochemistry	Europe	Mediterranean	Terr	Mech	Dynamic vegetation model
2006	Imhoff and Bounoua (2006)	Global	Climate change modelling	Any or global	Global	Terr	Mech	Biogeochemical model
2006	Janssen et al. (2006)	Generic	Ecology	Any or global	Global	All/no	ExKnow	Review
2006	Metzger and Schröter (2006)	Generic	Ecology	Europe	Europe	Terr	StatInf	Multi-indicator assessment
2006	Metzger et al. (2006)	Generic	Ecology	Any or global	Global	Terr	StatInf	Multi-indicator assessment
2006	Reynolds and Borlaug (2006)	Global	Agriculture	Any or global		Terr	ExKnow	Review
2006	Rounsevell et al. (2006)	Temp/Subt	Agriculture	Europe	Europe	Terr	StatInf	Distribution modelling
2006	Sathaye et al. (2006)	Global	Multi-disciplinary	Any or global	Global	All/no	ExKnow	Review
2006	Scholze et al. (2006)	Global	Ecology	Any or global	Global	Terr	Mech	Dynamic vegetation model
2007	Fraser (2007)	Global	Agriculture	Any or global	Many	Terr	Conc	
2007	Ito (2007)	Global	Biogeochemistry	Any or global	Global	Terr	Mech	Biogeochemical model
2007	Johnston and Williamson (2007)	Cold	Forestry	North America	Canada	Terr	Conc	
2007	Lagos (2007)	Trop	Multi-disciplinary	South America	Peru	Terr	ExKnow	Participatory/Workshop/Survey
2007	Manuel-Navarrete et al. (2007)	Subt	Multi-disciplinary	Central America	Caribbean	all/no	Conc	
2007	Ogden and Innes (2007)	Cold	Forestry	North America	Canada	Terr	ExKnow	Participatory/Workshop/Survey
2007	Pielke et al. (2007)	Global	Meteorology	Any or global	Global	Terr	Conc	
2007	Quetier et al. (2007)	Cold	Ecology	Europe	Europe	Terr	StatInf	Distribution modelling

Year	Author	Climate zone	Discipline	Continent	Country	Ecosystem type	Approach	Method
2007	Walsh and Kilsby (2007)	Cold	Hydrology	Europe	UK	Fresh	StatInf	Multi-indicator assessment
2007	Wilson et al. (2007)	Subt	Ecology	Australia	Australia	Terr	StatInf	Distribution modelling
2007	Wu et al. (2007)	Subt	Climate change modelling	Asia	China	Terr	Mech	Biogeochemical model
2008	Bachelet et al. (2008)	Global	Ecology	Any or global	Global	Terr	Mech	Dynamic vegetation model
2008	Berkhoff (2008)	Temp	Hydrology	Europe	Germany	Terr	Mech	Hydrologic model
2008	Chaturvedi et al. (2008)	Subt/Trop	Forestry	Asia	India	Terr	StatInf	Distribution modelling
2008	de Chazal et al. (2008)	Temp/Subt	Ecology	Europe	France	Terr	StatInf	Multi-indicator assessment
2008	Ericksen (2008)	Generic	Food system	Any or global	Generic	Terr	ExKnow	Review
2008	Körner and Jeltsch (2008)	Generic	Ecology	Any or global	Generic	All/no	Mech	Dynamic vegetation model
2008	Lasco et al. (2008)	Trop	Forestry	Asia	Philippines	Terr	ExKnow	Review
2008	Malone and Brenkert (2008)	Trop	Multi-disciplinary	Asia	India	Terr	StatInf	Multi-indicator assessment
2008	Metzger et al. (2008)	Temp/Subt	GIS and modelling	Europe	Europe	Terr	StatInf	Multi-indicator assessment
2008	Metzger et al. (2008)	Temp/Subt	GIS and modelling	Europe	Europe	Terr	StatInf	Multi-indicator assessment
2008	Nitschke and Innes (2008a)	Cold/Temp	Forestry	North America	Canada	Terr	Mech	Ecosystem model
2008	Nitschke and Innes (2008b)	Cold/Temp	Forestry	North America	Canada	Terr	StatInf	Multi-indicator assessment
2008	Nitschke and Innes (2008c)	Cold/Temp	Forestry	North America	Canada	Terr	StatInf	Multi-indicator assessment
2008	Palmer et al. (2008)	Global	Hydrology	Any or global	Global	Terr	Mech	Hydrologic model
2008	Reid et al. (2008)	Trop	Ecology	Africa	Namibia	Terr	StatInf	Statistical correlations
2008	Reidsma and Ewert (2008)	Temp/Subt	GIS and modelling	Europe	Europe	Terr	StatInf	Statistical correlations
2008	Schwinning et al. (2008)	Temp	Multi-disciplinary	North America	USA	Terr	ExKnow	Review
2009	Aguirre (2009)	Generic	Medicine	Any or global	Many	All/no	ExKnow	Review
2009	Alvarez-Filip et al. (2009)	Trop	Marine	Central America	Caribbean	Mar	ExKnow	Review
2009	Balshi et al. (2009)	Cold	Ecology	North America	Canada/USA	Terr	Mech	Biogeochemical model
2009	Decker and Conway (2009)	Generic	Ecology	North America	USA	Terr	StatInf	Statistical correlations
2009	Doherty et al. (2009)	Generic	Gen	Any or global	Global	All/no	ExKnow	Review

Year	Author	Climate zone	Discipline	Continent	Country	Ecosystem type	Approach	Method
2009	Finlayson et al. (2009)	Trop	Ecophysiology	Australia	Australia	Mar	Obs	
2009	Forbes et al. (2004)	Cold	Multi-disciplinary	Asia	Russia	All/no	Obs	
2009	Fraser and Stringer (2009)	Generic	Multi-disciplinary	Europe	Romania	All/no	Conc	
2009	Fyllas and Troumbis (2009)	Subt	Ecology	Europe	Mediterranean	Terr	Mech	Ecosystem model
2009	Joyce et al. (2009)	Generic	Gen	North America	USA	Terr	ExKnow	Review
2009	Kalame et al. (2009)	Trop	Ecology	Africa	Burkina Faso and Ghana	Terr	ExKnow	Review
2009	Lexer and Seidl (2009)	Subt	Ecology	Europe	Austria	Terr	Mech	Ecosystem model
2009	Littell et al. (2009)	Generic	Ecology	North America	USA	Terr	StatInf	Multi-indicator assessment
2009	McGregor et al. (2009)	Trop	Multi-disciplinary	Africa	Morocco	Terr	Obs	
2009	Omann et al. (2009)	Generic	Multi-disciplinary	Any or global	Many	All/no	ExKnow	Review
2009	Pizarro-Araya et al. (2009)	Generic	Multi-disciplinary	South America	Chile	Terr	Obs	
2009	Ripullone et al. (2009)	Subt	Ecology	Europe	Italy	Terr	Experi	Experiment
2009	Schroth et al. (2009)	Subt	Agriculture	Central America	Mexico	Terr	StatInf	Distribution modelling
2009	Sequist et al. (2009)	Subt/Trop	Multi-disciplinary	Africa	Sahel	Terr	Mech	Dynamic vegetation model
2009	Selkoe et al. (2009)	Temp/Subt	Ecology	North America	USA	Mar	Obs	
2009	Tenhunen et al. (2009)	Temp	Ecology	Europe	Austria	Terr	Mech	Biogeochemical model
2009	Tingem and Rivington (2009)	Trop	Agriculture	Africa	Cameroon	Terr	Mech	Crop model
2009	Tingem et al. (2009)	Trop	Agriculture	Africa	Cameroon	Terr	Mech	Crop model
2009	Watson et al. (2009)	Subt	Ecology	Australia	Australia	Terr	StatInf	Distribution modelling
2010	Bonebrake and Mastrandrea (2010)	Global	Ecology	Any or global	Global	Terr	StatInf	Climate statistics
2010	Brodie and Post (2010)	Cold	Ecology	North America	Canada/USA	Terr	StatInf	Statistical correlations
2010	Casalegno et al. (2010)	Cold	Ecology	Europe	Europe	Terr	StatInf	Distribution modelling
2010	Chapin et al. (2010)	Cold	Forestry	North America	USA	Terr	ExKnow	Review
2010	Clark et al. (2010)	Cold	Climate change modelling	Europe	UK	Terr	StatInf	Climate statistics

Year	Author	Climate zone	Discipline	Continent	Country	Ecosystem type	Approach	Method
2010	Dougill et al. (2010)	Subt	Climate change modelling	Africa	Botswana	Terr	Mech	Integrated model
2010	Eggermont et al. (2010)	Trop	Ecology	Africa	Uganda/DRC	Fresh	StatInf	Climate reconstruction
2010	Falloon and Betts (2010)	Cold	Agriculture	Europe	Europe	Terr	ExKnow	Review
2010	Gonzalez et al. (2010)	Global	Climate change modelling	Any or global	Global	Terr	Mech	Dynamic vegetation model
2010	Hirota et al. (2010)	Trop	Climate change modelling	South America	South America	Terr	Mech	Ecosystem model
2010	Hofmann and Todgham (2010)	Global	Ecology	Any or global	Global	All/no	ExKnow	Review
2010	Hultman et al. (2010)	Generic	Sociology	Any or global	Any or global	All/no	Conc	
2010	Johnson and Welch (2010)	Global	Fish	Any or global	Global	Mar	ExKnow	Review
2010	Johnson et al. (2010)	Cold	Hydrology	North America	Canada/USA	Terr	Mech	Ecosystem model
2010	La Sorte and Jetz (2010)	Montane	Ecology	Any or global	Global	Terr	StatInf	Distribution modelling
2010	Lasram et al. (2010)	Subt	Ecology	Europe	Mediterranean	Mar	StatInf	Distribution modelling
2010	Lindner et al. (2010)	Cold	Forestry	Europe	Europe	Terr	ExKnow	Review
2010	Littell et al. (2010)	Cold	Forestry	North America	USA	Terr	StatInf	Distribution modelling
2010	MacNeil et al. (2010)	Global	Fish	Any or global	Global	Mar	ExKnow	Review
2010	Menon et al. (2010)	Global	Ecology	Any or global	Global	Terr	Mech	Sea level rise model
2010	Pereira et al. (2010)	Global	Ecology	Any or global	Global	All/no	ExKnow	Review
2010	Yates et al. (2010)	Global	Ecology	Any or global	Global	Terr	StatInf	Distribution modelling
2011	Afreen et al. (2011)	Trop	Forestry	Asia	India	Terr	StatInf	Distribution modelling
2011	Alayon-Gamboa and Kuvira (2011)	Trop	Agriculture	Central America	Mexico	Terr	Obs	
2011	Bene et al. (2011)	Trop	Sociology	Africa	Mali and Nigeria	Terr	Obs	
2011	Brown and Westaway (2011)	Generic	Sociology	Any or global	Generic	Terr	Conc	
2011	Buytaert et al. (2011)	Trop	Ecology	Any or global	Topical highlands	Terr	ExKnow	Review
2011	Chaturvedi et al. (2011)	Trop	Forestry	Asia	India	Terr	Mech	Dynamic vegetation model

Year	Author	Climate zone	Discipline	Continent	Country	Ecosystem type	Approach	Method
2011	Corlett (2011)	Trop	Ecology	Any or global	Many	Terr	ExKnow	Review
2011	Czucz et al. (2011)	Generic	Ecology	Any or global	Generic	Terr	Conc	
2011	Dawson et al. (2011)	Generic	Ecology	Any or global	Generic	Terr	Conc	
2011	Garcia-Lopez and Allue (2011)	Temp/Subt	Forestry	Europe	Spain	Terr	StatInf	Multi-indicator assessment
2011	Gopalakrishnan et al. (2011)	Subt/Trop	Forestry	Asia	India	Terr	Mech	Dynamic vegetation model
2011	Laurance et al. (2011)	Trop	Ecology	Any or global	Tropics	Terr	Conc	
2011	Lin and Morefield (2011)	Temp	Multi-disciplinary	North America	USA	Terr	Conc	
2011	Lin et al. (2011)	Trop	Ecology	Asia	Taiwan	Terr	Obs	
2011	Mawdsley (2011)	Generic	Ecology	Any or global	Generic	Terr	Conc	
2011	Nori et al. (2011)	Trop	Ecology	multiple	N+S America	Terr	StatInf	Distribution modelling
2011	Preston et al. (2011)	Generic	Ecology	Any or global	Many	Terr	ExKnow	Review
2011	Purnomo et al. (2011)	Trop	Multi-disciplinary	Asia	Indonesia	Terr	StatInf	Multi-indicator assessment
2011	Ren et al. (2011)	Temp	Biogeochemistry	Asia	China	Terr	Mech	Biogeochemical model
2011	Robards et al. (2011)	Generic	Multi-disciplinary	Any or global	Generic	Terr	ExKnow	Review
2011	Rowland et al. (2011)	Generic	Ecology	Any or global	Generic	Terr	ExKnow	Review
2011	Seidl et al. (2011a)	Temp	Forestry	Europe	Austria	Terr	Mech	Ecosystem model
2011	Seidl et al. (2011b)	Temp	Forestry	Europe	Austria	Terr	Mech	Ecosystem model
2011	Sendzimir et al. (2011)	Subt/Trop	Multi-disciplinary	Africa	Sahel	Terr	Mech	Conceptual model
2011	Stratford et al. (2011)	Generic	Ecology	Any or global	Generic	Terr	Conc	
2011	Weiss and Alcamo (2011)	Subt/Trop	Hydrology	Europe	Europe	Terr	Mech	Hydrologic model
2011	Wertz-Kanounnikof et al. (2011)	Generic	Ecology	Any or global	Generic	Terr	Conc	
2012	Nolin (2012)	Temp	Hydrology	North America	USA	Terr	Mech	Agent-based model
2012	Prober et al. (2012)	Temp/Subt	Ecology	Australia	Australia	Terr	Conc	

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