European vulnerability to global change

a spatially explicit and quantitative assessment

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Abstract

This thesis presents a spatially explicit and quantitative vulnerability assessment for Europe, aimed at answering multidisciplinary, policy relevant questions about the vulnerability of the human-environment system to global change. Insights in vulnerability, defined as a function of potential global change impacts and the ability of humans to cope with these impacts, provides a basis for discussion between policymakers and stakeholders from different sectors about sustainable management of Europe's natural resources.

Within the ATEAM project (Advanced Terrestrial Ecosystem Analysis and Modelling) scenarios were constructed for a range of possible changes in socio-economic trends, land uses and climate (i.e. exposure). These scenarios were used as inputs in a suite of ecosystem models to assess the response of ecosystems and changes in the services they provide (i.e. potential impacts). In this thesis, the potential impacts of ecosystem service indicators for different sectors are placed in a consistent framework, and combined with a generic adaptive capacity index.

Results from the ATEAM vulnerability assessment show that global change will have a large influence on ecosystem service provision in Europe. There is however large heterogeneity in projected vulnerability between regions, sectors, and alternative development pathways. The Mediterranean region is projected to be the most vulnerable, while northwestern European countries face the lowest impacts and are indicated to have the greatest adaptive capacity.

Keywords

vulnerability assessment ; global change ; adaptive capacity ; Europe ; environmental stratification

Preface

This PhD thesis is the result of four years of work within the European Union (EU) 5th Framework Programme *Advanced Terrestrial Ecosystem Analysis and Modelling* (ATEAM). At the start of the project I was given the challenge to develop a framework for integrating the results from 14 ecosystem models in maps that show where in Europe people will be vulnerable to global change. This was exciting, because it meant bridging traditional disciplines and working with international research groups. It was not always easy to explain my conceptual ideas to the 40 project members, after copious Spanish or French lunches. But the critical comments and grunts, as well as the stimulating discussions and suggestions, were important in shaping the work presented in this thesis. Furthermore, they have taught me valuable lessons about scientific collaborations and communicating new ideas to a wider audience. I want to especially acknowledge Dagmar Schröter, the scientific coordinator of the project. She was a valuable support in the development of the vulnerability framework. Furthermore she was always there to support the importance of my work for the project. Without her support I may have despaired.

As part of the vulnerability framework I needed a quantitative classification defining principal environmental regions in Europe. This led to an intensive collaboration with Bob Bunce and colleagues from the research institute *Alterra* to develop the *Environmental Stratification of Europe*. At the time when the ATEAM project had unexpected delays, I was able to put a large part of my time in this side-product, including supervising MSc students and interns working on developing worked-examples of how the dataset can be applied, and describing the strata with ancillary information. For this I thank Rob Weber, Dani Guijarro Guasch, Vanessa Mateus, Anton Shkaruba, René-Luc d'Hondt, Emilie Kolodziejczyk, John Walsh, and Cláudia Rodrigues. It was both enjoyable and stimulating to work with Bob. His exceptional field expertise in environmental issues across Europe, combined with experience in aggregating such knowledge to the continental level, provided an eye-opening alternative to conventional approaches to continent-wide assessments, based on coarse datasets which ignore regional heterogeneity. I am pleased that Bob has become co-promotor to this thesis, as acknowledgement for the support and supervision he has provided. I want to thank Bob, Rob Jongman, Sander Mücher, and other colleagues from *Alterra* for their support and hope to be able to continue our collaboration in the future.

I carried out my research at the *Plant Production Systems Group*. Contents-wise my research was only marginally related to other research within the group. It therefore took some time to become familiar with its main body of research. The weekly lunch meetings, which I organized, helped in broadening my views on agricultural systems, and helped me to define my place within the group. When Frank Ewert and Pytrik Reidsma joined the group I was able to have more feedback on the ATEAM project. I much appreciate our discussions, both socially and scientifically. Most importantly perhaps, the colleagues of the Haarweg provided a positive working atmosphere. Jochem Evers and Barbara Sterk, with whom I shared the office for most of my research, were always there to give support and a listening ear in difficult periods, both in work and private life. Finally, I want to mention the enjoyable lunches with 'the lunch group', whose company outweighed the terrible food of the Zodiac canteen.

During the last four years I came to realize that the supervision I received was different from that of most of my fellow PhD students. I had only one official supervisor, Rik Leemans, who was also my promotor. There was no steering committee and no regularly scheduled of meetings. Rik was only in our building occasionally, and later on he was not even affiliated with our group any longer. Nevertheless, I am very happy with the supervision Rik provided. When I needed support, Rik was always available at short notice. He was always supportive and quick in providing feedback on manuscripts. Also, there were always sufficient resources for both travel and equipment. In addition, he gave me the freedom and support to develop my own ideas, including supporting the extensive collaboration with *Alterra*, outside the main course of my thesis. I therefore feel very lucky, and am thankful for his support.

Special thanks go to Bob Bunce, Rik Leemans and Dagmar Schröter for comments and suggestions on the papers in this thesis, to Gon van Laar for proof reading the manuscript, and to Mira Ouwehand for support in designing the cover.

Finally, I want to thank my family. While Tineke says the last four years have been less demanding on our family than she had expected, her support has certainly been conditional for finishing my PhD within four years. Tineke, Gonda, Tijkla, Hilde, Govert, Freek and Maarten, you have all given me excitement, pleasure, and love. This has helped me focus on my work during office hours and on you for the rest of my time.

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Chapter 1

General introduction

Wider context

We are facing global changes

Many aspects of our planet are changing rapidly due to human activity. Over the past 50 years, humans have changed ecosystems more rapidly and extensively than in any comparable period of time in human history, largely to meet rapidly growing demands for food, fresh water, timber, fibre, and fuel (Reid *et al.*, 2005). Under current projections of economic development and population growth, such changes are expected to continue the coming century. Furthermore, there is a growing consensus among scientists and the general public that the climate is changing (IPCC, 2001). All these changes, including a growing population and energy consumption, biodiversity loss, land use and climate change are strongly interrelated and cannot be seen in isolation. Because their impacts will influence the entire planet, the combined changes are now commonly recognized as global environmental change, or simply 'global change' (Steffen *et al.*, 2001).

In recent years, the impact of global change on society is frequently expressed by assessing potential impacts on ecosystem services. People obtain many benefits from ecosystems, including provisioning, regulating and cultural services. Changes in these ecosystem services will affect human well-being through impacts on security (Millennium Ecosystem Assessment, 2003). Because ecosystem service provision forms a direct link between ecosystems and society, the concept is especially useful for illustrating the need to employ mitigation or adaptation measures to prevent or alleviate impacts. Table 1.1a lists various ecosystem services that could be sensitive to global change. Some impacts of global change on ecosystem service provision have already been observed (e.g. decreases in agricultural productivity, fresh water provision, and biodiversity (Reid *et al.*, 2005)). Future scenarios project large changes in global change drivers such as global population and climate. In combination with socio-economic drivers these result in future scenarios that will have large impacts on society (Millennium Ecosystem Assessment, 2003). Some of these impacts will be directly caused by the global change drivers (e.g. through flooding or droughts), but in many cases human well-being will be affected by impacts on ecosystems and the services they provide, as illustrated in Table 1.1b.

Table 1.1. Ecosystem services are the benefits people obtain from ecosystems. Changes in these services affect human well-being through impacts on security, the basic material for a good life, health and social and cultural relations (Millennium Ecosystem Assessment, 2003). (a) Examples of ecosystem services. (b) Determinants and constituents of human well-being.

(a)

ecosystem services	
Supporting services	Soil formation
	Nutrient cycling
	Primary production
Provisioning services	Food
	Fresh water
	Fuel wood
	Fiber
	Biochemicals
	Genetic resources
Regulating services	Climate regulation
	Disease regulation
	Water purification
Cultural services	Spiritual and religious
	Recreation and tourism
	Cultural Heritage
	Educational

(b)

determinant and constituents of well-being	
Security	Ability to live in an environmentally clean and safe shelter
	Ability to reduce vulnerability to ecological shocks and stress
Basic material for a good life	Ability to access resources to earn income and gain livelihood
Health	Ability to be adequately nourished
	Ability to be free from avoidable disease
	Ability to have adequate and clean drinking water
	Ability to have clean air
	Ability to have energy to keep warm and cool
Good social relation	Opportunity to express aesthetic and recreational values associated with ecosystems
	Opportunity to express cultural and spiritual values associated with ecosystems
	Opportunity to observe, study, and learn about ecosystems

In order to anticipate the effects of global change, it is necessary to understand how global change processes interact, and how ecosystem service provision is affected by these processes. Because global change drivers differ between regions, depending on environmental and socio-economic conditions, it is important to understand where and when which impacts can be expected and who will be impacted. For instance, in Europe, population is expected to remain stable, or even decline, while globally population will grow (Nakicenovic *et al.*, 2000). And, southern Europe is projected to become drier, while northern Europe will probably become wetter (Ruosteenoja *et al.*, 2003). Dynamic global integrated impacts models such as IMAGE (IMAGE team, 2001) combine climate change scenarios with knowledge from other scientific disciplines, and can be used to explore potential impacts at the global scale. At more regional scales many studies and several complete assessments give more detailed insight for specific sectors or regions (e.g. Biggs *et al.*, 2004 ; Parry, 2000). For the European Union (EU), the ATEAM project currently forms the most advanced assessment, using state-of-the-art global change scenarios and ecosystem models to assess potential impacts of global change on agriculture, forestry, nature conservation, climate regulation, and hydrology (Schröter *et al.*, 2004).

Various measures try to prevent major impacts

As the term implies, global change is a worldwide concern that transcends national boundaries. Several international treaties have been ratified in an attempt to control specific global change impacts (Table 1.2). These conventions are supported by scientific insights into the global change process. Such insights have been gathered in two recent assessments: the *Intergovernmental Panel on Climate Change* (IPCC) *Third Assessment Report* (IPCC, 2001) and the *Millennium Ecosystem Assessment* (MA) (Reid *et al.*, 2005). Scientific evidence gathered by the IPCC showed that commitments in the *United Nations Framework Convention on Climate Change* (UNFCCC) would not be sufficient to prevent major impacts, and supported the development of the Kyoto Protocol (www.unfccc.org). It also showed that continued global warming is inevitable, and therefore adaptation will be important to cope with climate change. The MA was set up to strengthen capacity to manage ecosystems sustainably for human well-being. It directly supports the other international conventions.

The global conventions are important, because they recognize that global change processes could seriously threaten human well-being. The conventions form a first attempt towards preventing such negative impacts. However, resources and protective measures are limited, and these conventions will not be able to prevent negative impacts of global change on ecosystem service provision, and thus human well-being (Reid *et al.*, 2005). For many regions it is therefore important to assess how global change processes could influence their land. Such studies help nations or sectors develop adaptation strategies to cope with the impacts, or, when possible, mitigation measures to alleviate pressures from global change drivers.

Table 1.2. International conventions, aimed to reduce global change impacts, and the years in which they were ratified.

Convention	**year**
Convention on Wetlands (Ramsar)	1971
Convention on Migratory Species	1979
Framework Convention for the Protection of the Ozone Layer	1985
Convention on Biological Diversity	1992
Framework Convention on Climate Change	1992
Convention to Combat Desertification	1996

In the EU, several mitigation measures have been adopted. Best known is perhaps the Kyoto Protocol, under which the EU is committed to reduce greenhouse gas emissions by 8% in 2012, compared to 1990 levels. Another target of the EU is to stop biodiversity loss by 2010, as agreed during the *World Summit on Sustainable Development* in Johannesburg in 2002. Other mitigation measures include directives to limit pollution, e.g. stationary source emissions and water pollution. For land use change, the EU common agricultural policy (CAP) could be seen as a set of measures to alleviate pressures of change. Adaptation measures are developed for specific impacts of global change. These include widening rivers to cope with peak flows, and the construction of dams to retain water for drier summers; the construction of nature reserves and ecological networks to protect habitats and biodiversity; development of stress resistant crops to cope with extreme weather.

Current challenges in global change research

There is growing recognition that global change will have large impacts (IPCC, 2001 ; UNEP, 2002 ; Reid *et al.*, 2005), and even the United States Defense department is interested in potential global change impacts (Schwartz & Randall, 2003). Nevertheless, many uncertainties remain. First of all, these arise because the evolution of the driving forces of global change is highly uncertain. Scenarios, providing alternative images of how the future might unfold, form an appropriate tool with which to analyse global change processes. While the possibility that any single scenario will materialize is highly unlikely, a range of alternative scenarios can span a large range of uncertainty.

Further uncertainties arise from limitations in our current understanding of the climate system. While there is general agreement between the Global Climate Models (GCMs) about global mean temperature rise, there is considerable spatial variation in the projected changes. In addition, there is disagreement between the GCMs in projected changes in precipitation (Ruosteenoja *et al.*, 2003). Furthermore, the spatial and temporal resolution of the GCM outputs, while sufficient for global assessments, are coarse for assessing regional impacts of climatic change. Improved climate change projections, and higher spatial and temporal resolutions will increase confidence and applicability.

While climatic change can be projected with simplified assumptions about human behavior, global change drivers such as land use change and nitrogen deposition are directly influenced by local and national politics and individual land management decisions. Approximations can be made about the areas required to produce sufficient food for future population and the allocation of this land can be related to world-trade assumptions (IMAGE team, 2001 ; Rounsevell *et al.*, 2005), but spatial allocation and management is in the end determined by regional politics or decisions of individuals. Again, this leads to major uncertainties in projections of global change. Advanced techniques need to be developed that can better take into account irrational human behavior, as well as the implications of specific measures.

Traditional impact assessments explore potential impacts on ecosystems and human well-being, but ignore the possibility that both ecosystems and humans can adapt to new situations. For instance, agricultural productivity may be sensitive to changing climatic conditions, but new varieties of crops and improved irrigation management could mean that food security, farmer income and landscape character are hardly impacted. Residual impacts can therefore differ greatly from potential impacts, depending on the adaptive capacity. In some cases, this stems from autonomous adaptation by the natural or human systems (e.g. by farmers trying to use their land in the most profitable way). In other cases deliberate policy decisions, based on awareness of changing conditions, result in planned adaptation. Either way, stakeholders and policymakers will want to know whether impacts can be avoided through adaptation, thus reducing vulnerability to global change. At present, research into adaptive capacity is still in its early stages.

Scope, objectives, and structure of the thesis

Scope of the thesis

Given the uncertainties and limitations discussed above, it becomes a considerable challenge to provide policymakers and other stakeholders with information about indicators that are appropriate for their concerns. Scientific results need to be presented with attached uncertainties, but at the same time they should be presented in such a way that stakeholders feel that the findings are useful to them. One suggestion to make findings from global change science more relevant to stakeholders was given by Smith *et al.* (2001) in the *IPCC Third Assessment Report* (TAR). They suggest to explicitly include the ability to innovate and adapt in global change impact assessments. Under a similar potential impact, regions or sectors that are more able to adapt would then have a lower vulnerability.

The Chambers Dictionary (1993) defines vulnerability as the state of being '*physically or emotionally wounded or injured* [or] *open to successful attack*'. From this definition it is obvious that it is not pleasant to be vulnerable, and that one would wish to prevent or avoid being vulnerable, if at all possible. Stakeholders will be interested to know whether they are vulnerable to expected change, and policymakers will be interested in comparing the vulnerability of different sectors, or different regions. As such, appropriate indicators of vulnerability could provide a valuable framework for interpreting and comparing the effects of projected global change scenarios for different sectors and regions.

This thesis describes the vulnerability framework that was developed and applied within the EU 5th Framework Program *Advanced Terrestrial Ecosystem Analysis and Modelling* (ATEAM). In this project, a suite of ecosystem models was run with a set of internally consistent global change scenarios to produce European maps for changes in ecosystem service provision. Potential global change impacts were modelled for five sectors that rely on the provision of ecosystem services: agriculture, forestry, nature conservation, climate regulation, and hydrology. The project's focus was on indicators and impacts that were of interest, and could be modelled, at the European scale. Several stakeholder workshops, attended by national and EU level policymakers, and representatives from trade organizations and non-governmental organizations (NGOs), helped ensure the relevancy of the ATEAM results. The vulnerability framework, discussed in this thesis, integrates and compares impacts between sectors, and across regions.

Primary objectives of this thesis

1. The development of a methodology for quantifying and mapping vulnerability to global change impacts for Europe.

The vulnerability framework should integrate the results form the sectoral ecosystem models. It should allow for comparisons between ecosystem service indicators, between global changes scenarios and between different regions. In addition, some measure of adaptive capacity will need to be incorporated. Finally, implementation of the vulnerability framework should be consistent for all indicators, and relatively straightforward, as the project generated large amounts of data.

2. The analysis of the model outputs from the ATEAM ecosystem models, reporting on the vulnerability of different sectors and regions to global change.

The results must be presented in such a way that they can be interpreted by stakeholders with limited scientific training. It should always be possible to retrieve the original data, but insights about vulnerability should be synthesized for larger regions in order to extract some key messages.

Secondary objective of this thesis

During the development of the vulnerability framework it became apparent that in order to make comparisons across Europe, some form of environmental stratification was required. Because no suitable stratification was available at the time, the creation of such a dataset was necessary.

3. The construction of a suitable quantitative stratification of Europe in principal environmental strata.

A suitable stratification should distinguish main European environments unambiguously by specific variables. It is important that the distinguished strata correlate with important environmental variables and ecosystem services. Finally, it should be possible to relate the stratification to the ATEAM global change scenarios in order to also stratify projected future conditions.

Structure of the thesis

Chapter 2 presents the methodology for quantifying and mapping vulnerability for Europe using the outputs from the ATEAM ecosystem models. The chapter synthesizes the main findings of the vulnerability assessment, and shows that there are differences in vulnerability across sectors and between regions. The *ATEAM vulnerability mapping tool* (Metzger *et al.*, 2004), available on the CD-ROM annex to this thesis, provides all maps that were used in the paper, and allows stakeholders make their own analyses.

In Chapter 3 the land use types which were modelled in the ATEAM land use change scenarios were linked to various ecosystem services. For instance, forestry land use was directly related to the ecosystem service indicator *fibre production*. The resulting indicators were subsequently analysed with the ATEAM vulnerability framework. Large differences between future scenarios illustrate how both policy and society play an important role in determining eventual residual impacts.

Chapter 4 illustrates how the vulnerability framework can also be applied to results form other global change impacts models, when a suitable stratification system is available. Here outputs for the *total agricultural production* indicator from the global IMAGE model (IMAGE team, 2001) were stratified by global biomes.

Chapter 5 presents the *Environmental Stratification of Europe* (EnS) which was used in the vulnerability framework to facilitate comparisons in the ecosystem service indicators across the European environment. Chapter 6 shows how climate functions were calculated for the EnS strata to model their future distribution.

Chapter 7 gives a general discussion of the vulnerability framework and the results of the ATEAM vulnerability assessment. Especially Mediterranean Europe is vulnerable to global change, while Atlantic Europe has a higher indicated adaptive capacity, and lower potential impacts. There is however considerable variability in vulnerability, and there are large uncertainties.

Colour figures have been placed together on 16 colour plates in the back of the thesis (pages 161-176). Figure names of such colour figures start CP.

References

Biggs R, Bohensky E, Desanker PV, Fabricius C, Lynam T, Misselhorn AA, Musvoto C, Mutale M, Reyers B, Scholes RJ, Shikongo S, Jaarsveld AS van (2004) The South African Millennium Ecosystem Assessment – integrated report. Council for Scientific and Industrial Research, Pretoria, South Africa.

Chambers Dictionary (1993) Chambers Dictionary. Chambers Harrap Publishers, Edinburgh, UK.

IPCC (2001) Climate Change 2001: Synthesis Report. Contribution of Working Groups I , II and III to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

IMAGE team (2001) The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate change and impacts in the 21st century. National Institute of Public Health and the Environment (RIVM), Bilthoven, The Netherlands.

Millennium Ecosystem Assessment (2003) Ecosystems and Human Well-being: a framework for assessment. Island Press, Washington DC, USA.

Metzger MJ, Leemans R, Schröter D, Cramer W, the ATEAM consortium (2004) The ATEAM vulnerability mapping tool. Quantitative Approaches in Systems Analysis No. 27, CD-ROM publication, Office C.T. de Wit Graduate School for Production Ecology & Resource Conservation (PE&RC), Wageningen, The Netherlands. [Available on the CD-ROM annex to this thesis]

Nakicenovic N, Alcamo J, Davis G, Vries B de, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, la Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, Rooyen S van, Victor N, Dadi Z (2000) IPCC Special Report on Emission Scenarios (SRES). Cambridge University Press, Cambridge, UK.

Parry M (ed) (2000) Assessment of Potential Effects and Adaptations fro Climate Change in Europe: The Europe ACACIA Project. Jackson Environment Institute, University of East Anglia, Norwich, UK.

Reid WV, Mooney HA, Cropper A, Capistrano D, Carpenter SR, Chopra K, Dasgupta P, Dietz T, Duraiappah AK, Hassan R, Kasperson R, Leemans R, May RM, McMichael AJ, Pingali P, Samper C, Scholes R, Watson RT, Zakri AH, Shidong Z, Ash NJ, Bennett E, Kumar P, Lee MJ, Raudsepp-Hearne C, Simons H, Thonell J, Zurek MB (2005) Millennium Ecosystem Assessment Synthesis report. Island Press, Washington DC, USA.

Rounsevell MDA, Ewert F, Reginster I, Leemans R, Carter TR (2005) Future scenarios of European agricultural land use II. Projecting changes in cropland and grassland. Agriculture Ecosystems and Environment 107: 117-135.

Ruosteenoja K, Carter TR, Jylhä K, Tuomenvirta H (2003) Future climate in world regions: an intercomparison of model-based projections for the new IPCC emission scenarios. The Finnish Environment 644. Finnish Environment Institute, Helsinki, Finland.

Schröter D, Acosta-Michlik L, Arnell AW, Araújo MB, Badeck F, Bakker M, Bondeau A, Bugmann H, Carter T, Vega-Leinert AC de la, Erhard M, Espiñeira GZ, Ewert F, Friedlingstein P, Fritsch U, Glendining M, Gracia CA, Hickler T, House J, Hulme M, Klein RJT, Krukenberg B, Lavorel S, Leemans R, Lindner M, Liski J, Metzger MJ, Meyer J, Mitchell T, Mohren F, Morales P, Moreno JM, Reginster I, Reidsma P, Rounsevell MDA, Pluimers J, Prentice IC, Pussinen A, Sánchez A, Sabaté S, Sitch S, Smith B, Smith J, Smith P, Sykes MY, Thonicke K, Thuiller W, Tuck G, Werf G van der, Vayreda J, Wattenbach M, Wilson DW, Woodward FI, Zaehle S, Zierl B, Zudin S, Cramer W (2004) The ATEAM final report 2004 – Detailed report related to overall project duration. Advanced Terrestrial Ecosystem Analysis and Modelling, a project funded under the 5th Framework Programme of the European Union. [www.pik-potsdam.de/ateam/]

Smith JB, Schellnhuber H-J, Qader Mirza M, Fankhauser S, Leemans R, Erda L, Ogallo LA, Pittock BA, Richels R, Rosenzweig C, Safriel U, Tol RSJ, Weyant J, Yohe G (2001) Vulnerability to Climate Change and reasons for concern: A Synthesis. In: McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (eds) Climate Change 2001. Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, UK, pp 913-967.

Steffen W, Tyson P, Jäger J, Matson P, Moore B, Oldfield F, Richardson K, Schelnhuber J, Turner BL, Wasson R (2001) Global change and the earth system: a planet under pressure. IGBP Science 4: 2-32.

Schwartz P, Randall D (2003) An abrupt climate change scenario and its implications for United States national security. A report of the Global Business Network, commissioned by the U.S Defense department. [http://www.ems.org/climate/pentagon_climate_change.pdf]

UNEP (2002) GEO-3: Global Environmental Outlook Report 3. UNEP - United Nations Environment Programme.

Chapter 2

European vulnerability to changes in ecosystem service provision

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Abstract

This chapter presents a spatially explicit and quantitative vulnerability assessment for Europe, aimed at answering multidisciplinary policy relevant questions about the vulnerability of the human-environment system to global change. Within the ATEAM project (Advanced Terrestrial Ecosystem Analysis and Modelling) scenarios were constructed for a range of possible changes in socio-economic trends, land uses and climate (i.e. exposure). These scenarios were used as inputs in a range of ecosystem models to assess the response of ecosystems and changes in the services they provide (i.e. potential impacts). In this study, the potential impacts of ecosystem services for four sectors are placed in a consistent framework, and combined with a generic adaptive capacity index. By allowing analysis of different sectors, regions and development pathways the vulnerability assessment can provide the basis for discussion between stakeholders and policymakers about sustainable management of Europe's natural resources.

Introduction

Many aspects of our planet are changing rapidly because of to human activities and these changes are expected to accelerate during the next decades (Steffen *et al.*, 2001). For example, forest area in the tropics is declining, many species are threatened with extinction, and rising atmospheric carbon dioxide results in global warming (Reid *et al.*, 2005). Many of these changes will have an immediate and strong effect on agriculture, forestry, biodiversity, human health and well-being, and on amenities such as traditional landscapes (Watson *et al.*, 2000 ; UNEP, 2002, Reid *et al.*, 2005). Furthermore, a growing global population, with increasing per capita consumption of food and energy, are expected to continue emitting pollutants to the atmosphere, resulting in continued nitrogen deposition and eutrophication of environments (Galloway, 2001 ; Alcamo, 2002). In the face of these changes, it is important to integrate and extend current operational systems for monitoring and reporting on environmental and social conditions (cf Kates *et al.*, 2001). Over the last decades many people have become increasingly aware of these environmental changes, such that they are now commonly recognized as 'global change' (Steffen *et al.*, 2001). Many research projects and several environmental assessments are currently addressing these concerns at all relevant scales, frequently in multidisciplinary collaborations. However, integrating this wealth of information across disciplines remains a considerable challenge (Millennium Ecosystem Assessment, 2003).

Ecosystem services form a vital link between ecosystems and society by providing provisional services (e.g. food, timber, medicines and fuels), regulating services (e.g. climate regulation and water purification), cultural services (e.g. aesthetic values, sense of place) and supporting services (e.g. nutrient cycling and climate regulation) (Daily, 1997 ; Millennium Ecosystem Assessment, 2003). Impacts of global change, including land use change, on ecosystems have already been observed (see reviews by Geist & Lambin, 2002 ; Parmesan & Yohe, 2003 ; Root *et al.*, 2003) and influence human society. In addition to immediate global change effects on humans (e.g. sea-level rise or droughts), an important part of human vulnerability to global change is therefore caused by impacts on ecosystems and the services they provide (Millennium Ecosystem Assessment, 2003).

The *Synthesis* chapter (Smith *et al.*, 2001) of the *Intergovernmental Panel on Climate Change* (IPCC) *Third Assessment Report* (TAR) recognized the limitations of traditional impact assessments, where a few climate-change scenarios are used to assess the response of a system at a future time. Smith *et al.* (2001) challenged the scientific community to move towards more transient assessments that are a function of shifting environmental parameters (including climate) and socio-economic trends, and explicitly include the ability to innovate and adapt to the resulting changes. A step towards meeting this challenge is their definition of 'vulnerability':

Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes (IPCC TAR).

Although this definition addresses climate change only, it already includes susceptibility, which is a function of exposure, sensitivity, and adaptive capacity. The vulnerability concept developed for ATEAM is a further elaboration of this definition and was developed especially to integrate results from a broad range of models and scenarios. Projections of changing supply of different ecosystem services and scenario-based changes in adaptive capacity are integrated into vulnerability maps for different socio-economic sectors (agriculture, forestry, climate regulation, and nature conservation) (Schröter *et al.*, 2004 ; 2005b). This chapter demonstrates how these vulnerability maps provide a means of making comparisons between ecosystem services, sectors, scenarios and regions to tackle questions such as:

- Which regions are most vulnerable to global change ?
- How do the vulnerabilities of two regions compare ?
- Which sectors are the most vulnerable in a certain region ?

- Which scenario is the least harmful for a sector ?

The following sections first summarize the concepts of the spatially explicit and quantitative framework for a vulnerability assessment for Europe. Then, results from the assessment are presented per socio-economic sector, followed by a comparison between the sectors across principal European environmental zones.

Methods

The concept of vulnerability

As a starting point for the ATEAM vulnerability concept, the IPCC definitions of vulnerability to climate change, and related terms such as exposure, sensitivity, and adaptive capacity, were broadened in order to consider not only climate change, but also other global changes such as land use change. Table 2.1 lists the definitions of some fundamental terms used in this chapter and gives an example of how these terms could relate to climate regulation by ecosystems. From these definitions the following generic functions are constructed, describing the vulnerability of a sector relying on a particular ecosystem service at a particular location (e.g. grid cell) under a certain scenario and at a certain point in time. Vulnerability is a function of exposure, sensitivity and adaptive capacity (equation 1). Potential impacts are a function of exposure and sensitivity (equation 2). Therefore, vulnerability is a function of potential impacts and adaptive capacity (equation 3):

$$V(es, x, s, t) = f\,(\,E(es, x, s, t), S(es, x, s, t), AC(es, x, s, t)\,) \qquad (1)$$

$$PI(es, x, s, t) = f\,(\,E(es, x, s, t), S(es, x, s, t)\,) \qquad (2)$$

$$V(es, x, s, t) = f\,(\,PI(es, x, s, t), AC(es, x, s, t)\,) \qquad (3)$$

where V = vulnerability, E = exposure, S = sensitivity, AC = adaptive capacity and PI = potential impact, es = ecosystem service, x = a grid cell, s = a scenario, t = a time slice

These simple conceptual functions describe how the different elements of vulnerability are related to each other. Nevertheless, they are not immediately operational for converting maps of ecosystem services into vulnerability maps. The following sections illustrate how vulnerability is quantified and mapped in the present study, using one ecosystem service indicator, ***net carbon storage***, as an example.

Table 2.1. Definitions of important terminology related to vulnerability, with an example for the climate regulation. IPCC TAR = Intergovernmental Panel on Climate Change Third Assessment Report (IPCC 2001).

Term		ATEAM definitions based on IPCC TAR	Part of the assessment	Carbon storage example
Exposure	**(E)**	The nature and degree to which ecosystems are exposed to environmental change.	Scenarios	Temperature rise, increased droughts
Sensitivity	**(S)**	The degree to which a human-environment system is affected, either adversely or beneficially, by environmental change.	Ecosystem Models	Amount of carbon stored by ecosystems
Adaptation	**(A)**	Adjustment in natural or human systems to a new or changing environment.		Changes in local management, change in tree species
Potential Impact	**(PI)**	All impacts that may occur given projected environmental change, without considering planned adaptation.		Some loss of Carbon by forest fires
Adaptive Capacity	**(AC)**	The potential to implement planned adaptation measures.	Vulnerability Assessment	Capacity to implement better fire management
Vulnerability	**(V)**	The degree to which an ecosystem service is sensitive to global change plus the degree to which the sector that relies on this service is unable to adapt to the changes.		Increased probability of carbon losses through increased fire risk and inability to adapt to this by e.g. changing land cover to less fire prone forests (e.g. exchange Eucalyptus plantations with native forests)
Planned Adaptation	**(PA)**	The result of a deliberate policy decision based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain or achieve a desired state.	The future will tell.	Better fire management
Residual Impact	**(RI)**	The impacts of global change that would occur after considering planned adaptation.		Carbon loss to forest fires

Exposure, Sensitivity and Potential impacts

The IPCC projections of the main global change drivers, based on the *Special Report on Emissions Scenarios* (SRES) (Nakicenovic *et al.*, 2000) were used to represent exposure. SRES consists of a comprehensive set of narratives that define the local, regional and global socio-economic driving forces of environmental change (e.g. demography, economy, technology, energy, and agriculture). The SRES storylines were structured in four major 'families' labelled A1, A2, B1 and B2, each of which emphasises a largely different set of social and economic development pathways, organized along two axes. The vertical axis represents a distinction between more economically (A) and more environmentally and equity (B) orientated futures. The horizontal axis represents the range between more globalization (1) and more regionally-oriented developments (2). Ewert *et al.*, (2005) give a summary of the derived characteristics of the scenario families, relevant for land use change.

Scenarios were developed for atmospheric carbon dioxide concentration, climate (Mitchell *et al.*, 2004), socio-economic variables, and land use (Rounsevell *et al.*, 2005ab ; Ewert *et al.* 2005). These scenarios are internally consistent, and considered explicitly the global context of European land use (i.e. import and export of agricultural goods). The IMAGE implementation (IMAGE team, 2001) of these scenarios was used to define the global context (trade, socio-economic trends, demography, global emissions and atmospheric concentrations, climate change levels). The high-resolution (10 arcmin x 10 arcmin, approximately 16 km x 16 km in Europe) land use change scenarios used in this vulnerability assessment were derived from an interpretation of the SRES storylines. The vulnerability assessment spans a wide range of plausible futures for three time slices (1990-2020, 2020-2050, 2050-2080).

Ecosystem service provision was estimated by ecosystem models as a function of ecosystem sensitivity and global change exposure. Schröter *et al.* (2004 ; 2005b) discuss these models, and the projected changes in ecosystem service provision, in more detail. The resulting range of outputs for each ecosystem service indicator enabled the differentiation of regions that are impacted under most scenarios, regions that are impacted under specific scenarios, and regions that are not impacted under any scenario.

The example maps in this manuscript are restricted to the ecosystem service indicator *net carbon storage* (Fig. CP1.1). For this ecosystem service indicator, the vulnerability approach is illustrated with maps for one scenario, the A1 scenario, which assumes continued globalisation with a focus on economic growth. The analysis of multiple scenarios is discussed at the end of this section.

Stratified potential impacts

The estimation of potential impacts is undertaken at the regional scale, emphasising the differences across the European environment. Simply comparing changes in ecosystem services across Europe provides only a limited analysis of regional differences because ecosystem services are highly correlated with their environments. Some environments have high values for particular ecosystem services, whereas other regions have lower values. For instance, Spain has high biodiversity, but low grain yields, whereas The Netherlands has a far lower biodiversity, but a very high grain yield. Therefore, while providing useful information about the stock of resources at a European scale, absolute differences in species numbers or yield levels are not good measures for comparing regional impacts between these countries. Looking at relative changes would overcome this problem (e.g. –40% arable land in Mediterranean south *versus* +8% in the Boreal), but also has a serious limitation: the same relative change can occur in very different situations. Table 2.2 illustrates how a relative change of –20% can represent very different impacts, both between and within environments. Therefore comparisons of relative changes in single grid cells must be interpreted with great care.

For a meaningful comparison of grid cells across Europe it is necessary to place potential impacts in their regional environmental context, i.e. in an environmental envelope, or stratum, that is suited as a reference for the values in an individual grid cell. Because environments will alter under global change, consistent environmental strata must be determined for each time slice. The recently developed *Environmental Stratification of Europe* (EnS) was used to stratify the modelled potential impacts (Chapter 5 ; Metzger *et al.*, 2005). The EnS was created by statistical clustering of selected climate and topographical variables into 84 strata. For each stratum a discriminant function was calculated for the variables available from the climate change scenarios. With these functions the 84 climate classes were mapped for the different Global Climate Models (GCMs), scenarios and time slices, resulting in 48 maps of shifted climate classes. Maps of the EnS, for baseline and the HadCM3-A1 scenario are mapped in Fig. CP1.2 for aggregated Environmental Zones (EnZs). With these maps, all modelled potential impacts on ecosystems can be placed consistently in their environmental context.

Table 2.2. Example of changing ecosystem service supply (e.g. grain yield in t ha^{-1} y^{-1}) in four grid cells and two different environments between two time slices (t and t+1). The potential to supply the ecosystem service decreases over time in environment 1, and increases over time in environment 2. The 'Value in a grid cell' is the ecosystem service supply under global change conditions as estimated by an ecosystem model. The relative change in ecosystem service may not form a good basis for analysing regional potential impacts, in this example it is always –20%. When changes are stratified by their environment, comparison of potential impacts in their specific environmental context is possible. The 'Stratified potential impact' is the 'Value in a grid cell' divided by the 'Highest ecosystem service value' in a specific environmental stratum at a specific time slice (see text). Note that in grid cell B, PIstr is 0.0 even though ES decreases because relative to the environmental condition, ecosystem service provision is constant (see text).

	environment 1				environment 2			
	grid cell A		grid cell B		grid cell C		grid cell D	
	t	t+1	t	t+1	t	t+1	t	t+1
Ecosystem service provision (ES)	3.0	2.4	1.0	0.8	8.0	6.4	5.0	4.0
Absolute change		**–0.6**		**–0.2**		**–1.6**		**–1.0**
Relative change (%)		**–20**		**–20**		**–20**		**–20**
Highest ecosystem service value (ESref)	3.0	2.7	3.0	2.7	8.0	8.8	8.0	8.8
Stratified ecosystem service provision (ESstr)	1.0	0.9	0.3	0.3	1.0	0.7	0.6	0.5
Stratified potential impact index (PIstr)		**–0.1**		**0.0**		**–0.3**		**–0.1**

Within an environmental stratum, ecosystem service indicators can be expressed relative to a reference value. While any reference value is inevitably arbitrary, in order to make comparisons it is important that the stratification is performed consistently. The reference value used in this assessment is the highest ecosystem service value achieved in an environmental stratum. This measure can be compared to the concept of potential yield, defined by growth-limiting environmental factors (Ittersum van *et al.*, 2003). For a grid cell in a given EnS stratum, the fraction of the modelled ecosystem service provision relative to the highest achieved ecosystem service value in the region (ESref) is calculated, giving a stratified value of the ecosystem service provision (ESstr) with a 0–1 range for the ecosystem service in the grid cell:

$$ESstr_{(es,\,x,\,s,\,t)} = ES_{(es,\,x,\,s,\,t)} \,/\, ESref_{(es,\,ens,\,x,\,s,\,t)} \quad (4)$$

where ESstr = stratified ecosystem service provision, ES = ecosystem service provision and ESref = highest achieved ecosystem service value, es = ecosystem service, x = a grid cell, s = a scenario, t = a time slice and ens = an environmental stratum

In this way a map is created in which potential impacts on ecosystem services are stratified by their environment and expressed relative to a reference value (Fig. CP2.1). Because the environment changes over time, both the reference value and the environmental stratification are determined for each time slice. As shown in Fig. CP2.1, the stratified ecosystem service provision map shows more regional detail than the original non-stratified map. This is the regional detail required to compare potential impacts across regions (see also Table 2.2). The change in stratified ecosystem service provision compared to baseline conditions shows how changes in ecosystem services affect a given location (see also Table 2.2). Regions where ecosystem service supply increases relative to the environment have a positive change in potential impact and *vice versa* (see Fig. CP2.2). This change in ESstr (equation 5) gives a measure of stratified potential impact (PIstr), which is used to estimate vulnerability (see below).

$$PIstr_{(es,\,x,\,s,\,t)} = ESstr_{(es,\,x,\,s,\,t)} - ESstr_{(es,\,x,\,s,\,baseline)} \quad (5)$$

where PIstr = stratified potential impact, ESstr = stratified ecosystem service provision, es = ecosystem service, x = a grid cell, s = a scenario, t = a time slice, baseline = 1990

Adaptive capacity index

Adaptation in general is understood as an adjustment in natural or human systems in response to actual or expected environmental change, which moderates harm or exploits beneficial opportunities. Here, adaptive capacity reflects the potential to implement planned adaptation measures and is, therefore, concerned with deliberate human attempts to adapt to or cope with change. ‘Autonomous adaptation’ by contrast, does not constitute a conscious response (e.g. spontaneous ecological changes). The concept of adaptive capacity was introduced in the *IPCC TAR* (IPCC, 2001), according to which the factors that determine adaptive capacity to climate change include economic wealth, technology and infrastructure, information, knowledge and skills, institutions, equity and social capital. Thus far, only one study has made an attempt at quantifying adaptive capacity based on observations of past hazard events (Yohe & Tol, 2002). For the vulnerability assessment framework, present-day and future estimates of adaptive capacity were sought that would be quantitative, spatially explicit, and based on, as well as consistent with, the different exposure scenarios described above. Thus a generic index was developed of macro-scale adaptive capacity. This index was based on a conceptual framework of socio-economic indicators, determinants and components of adaptive capacity, e.g. GDP per capita, female activity rate, equity, number of patents, and age dependency ratio (Schröter *et al.*, 2003 ; Klein *et al.*, in prep.). The index was calculated for smaller regions (i.e. provinces and counties) and differs for each SRES storyline. The index does not include the ability of individuals to adapt. An illustrative example of the spatially-explicit, generic adaptive capacity index over time is given in Fig. CP3.1, for the A1 scenario. Different regions in Europe show different adaptive capacities – under this scenario, lowest adaptive capacity is expected in the Mediterranean, but the differences decline over time.

Vulnerability maps

The different elements of the vulnerability function (equation 3) have now been quantified. The last step, the combination of the stratified potential impact (PIstr) and the adaptive capacity index (AC), is however the most difficult step, especially when taking into account the limited empirical basis of the adaptive capacity index. It was therefore decided to create a visual combination of PIstr and AC without quantifying a specific relationship between them. The vulnerability maps illustrate which areas are vulnerable. For further analytical purposes the constituents of vulnerability, the changes in potential impact and the adaptive capacity index, are viewed separately.

Trends in vulnerability follow the trend in PIstr: when ecosystem service supply decreases, humans relying on that particular ecosystem service become more vulnerable in that region. Alternatively, vulnerability decreases when ecosystem service supply increases. Adaptive capacity lowers vulnerability. In regions with similar changes in potential impact, a region with a high AC will be less vulnerable than a region with a low AC. The PIstr determines the Hue, ranging from red (decreasing ecosystem service provision, PIstr = –1, highest negative potential impact) through yellow (no change in ecosystem service provision, PIstr = 0, no potential impact) to green (increase in ecosystem service provision, PIstr = 1, highest positive potential impact). Note that it is possible that while the modelled potential impact remains unchanged, the stratified potential impact increases or decreases due to changes in the highest value of ecosystem service supply in the environmental class (ESref). Thus, when the environment changes, this is reflected in the potential impact.

Adaptive capacity determines colour saturation and ranges from 50% to 100% depending on the level of the AC. When the PIstr becomes more negative, a higher AC will lower the vulnerability, therefore a higher AC value has a lower saturation, resulting in a less bright shade of red. Alternatively, when ecosystem service supply increases (PIstr > 0), a higher AC value has a higher saturation, resulting in a brighter shade of green. Conversely, in areas of negative impact, low AC gives brighter red, whereas in areas of positive impacts low AC gives less bright green. Fig. CP3.2 shows the vulnerability maps and the legend for *farmer livelihood* under the A1 scenario for the HadCM3 GCM. Under this scenario *farmer livelihood* decreases in extensive agricultural areas. The role of AC becomes apparent in rural France and Spain, where France is less vulnerable than Spain due to a higher AC, i.e. a supposed higher ability of the French agricultural sector to react to these potential impacts.

Selected ecosystem services

This chapter aims to quantify global change concerns for ecosystem service indicators for four sectors: agriculture, forestry, nature conservation, and climate regulation. These sectors rely on the sustainable supply of ecosystem services, which can therefore be used as a measure of human well-being under the influence of global change threats. This is similar to the approach used by Luers *et al.* (2003) in looking at the vulnerability of Mexican farmers to decreasing wheat yields arising from climate damage and market fluctuations.

The ecosystem service indicators were selected in a close consultation process with stakeholders from sectors relying on these ecosystem services (see also Vega-Leinert *et al.*, 2005.). Schröter *et al.* (2004, 2005b) discuss these ecosystem service indicators in more detail. Table 2.3a briefly explains the indicators which are analysed in the ATEAM vulnerability assessment. Different ecosystem modelling techniques are used for different sectors, but all ecosystem models (listed in Table 2.3b), use the same set of internally consistent input scenarios for climate change and land-use change.

Several ecosystem services modelled by the ATEAM project could not be incorporated in this vulnerability assessment, because the output could not be converted into maps of stratified potential impact. The EFISCEN forestry model (Nabuurs *et al.*, 2000 ; Karjalainen *et al.*, 2002) does not produce results on the ATEAM grid, but output on national or province level. The biodiversity indicator *species turnover* already compares projected values with baseline conditions, making stratification for the two time slices impossible. The outputs from the hydrological model Mac-pdm (Arnell, 1999 ; Arnell, 2003) do not correlate with the Environmental Stratification, and therefore produce meaningless results when used in the vulnerability framework presented here. For climate regulation it is important to look at both *net carbon storage* and *net carbon emission* (together *Net Ecosystem Exchange*). Because *net carbon emission* is a disservice, the PIstr values are multiplied by –1: increased emission is negative, while decreased emission is positive.

Table 2.3. (a) Sectors, ecosystem services they rely on and indicators for these ecosystem services that were chosen together with stakeholders. (b) Ecosystem models used in ATEAM to model changes in ecosystem services, listed per sector.

(a)

Sector	**Service**	**Indicator**
Agriculture	Framer livelihood Soil fertility maintenance	Agricultural land area Soil organic carbon content
Forestry	Wood production Wood supply	Net annual stem wood increment Net annual felling
Carbon storage	Climate protection	Net biome production, divided in Net carbon storage and net carbon emission
Biodiversity and nature conservation	Beauty Life support processes	Species richness (plants, trees, birds, herptiles)

(b)

Sector	**Model**	**Reference**
Agriculture	Land use change scenarios SUNDIAL ROTHC	(Rounsevell *et al.*, 2005ab) (Ewert *et al.*, 2005) (Smith *et al.*, 1996) (Coleman & Jenkinson, 1996; Coleman *et al.*, 1997)
Forestry	GOTILWA+	(Sabaté *et al.*, 2002)
Carbon storage	LPJ (biogeochemistry)	(Sitch *et al.*, 2003; , fire dynamics: Venevsky *et al.*, 2002)
Biodiversity and nature conservation	statistical niche modelling	(Araújo *et al.*, 2002; Thuiller, 2003)

Analysis of the results

Each vulnerability map gives an intuitive overview for an ecosystem service indicator for one scenario and for one time slice. It is however difficult to analyse the effects of the four scenarios on the multiple ecosystem service indicators for a multitude of vulnerability maps. Furthermore, because the legend of these maps is two-dimensional (adaptive capacity and stratified potential impact), it is difficult to analyse the cause of the vulnerability. For a comprehensive way of analysing the vulnerability maps it is necessary to look at AC and PIstr separately. Furthermore, it can be important to look at the original maps of the modelled ecosystem service provision, or at the global change scenarios, in order to fully understand the vulnerabilities between different sectors and regions in Europe.

To facilitate analysis of the many maps created by the ATEAM project, including the scenarios, maps of ecosystem service provision and adaptive capacity, a separate software tool was developed (Metzger *et al.*, 2004). This digital atlas offers both the scientific community and other stakeholders access to the project's results. The *ATEAM vulnerability mapping tool* generates fact sheets for each selected map, providing essential background information to help interpret the map. Furthermore, the software provides some simple analysis functionality, e.g. zooming to countries or Environmental Zones, simple map queries, and generating scatter plots summarize multiple maps. The *ATEAM vulnerability mapping tool* is available on the CD-ROM annex to this thesis.

An effective method of analysing multiple maps is by creating scatter plots that summarise mean values of multiple maps for different regions, e.g. for different Environmental Zones, and the four time slices (cf Fig. 2.1), or maps for the four storylines summaries per Environmental Zone for 2080 (cf Fig. 2.2). Such scatter plots help analyse differences across regions, time slices, and alternative storylines. Furthermore, scatter plots can be used to analyse the variability in model outputs for different GCMs. The *ATEAM vulnerability mapping tool* allows users to create such scatter plots.

Results

Results from the vulnerability assessment are presented below for the 2080 time slice as scatter plots, summarizing adaptive capacity and stratified Potential impacts for the four storylines across principal Environmental Zones. As discussed before, individual vulnerability maps, as well as other maps generated by the ATEAM project, are available in the *ATEAM vulnerability mapping tool* (Metzger *et al.*, 2004), which also allow results to be presented per country. In the *Discussion*, the adaptive capacity and potential impact results will be used to draw more general conclusions about the European vulnerability to changes in ecosystem service provision.

Adaptive capacity

The capacity of different countries and regions in Europe to cope with the effects of global change is projected to increase in the coming century, mainly as a result of assumed economic growth. While gross domestic product (GDP) growth is projected for all countries, countries that currently have a lower adaptive capacity (e.g. the Mediterranean countries) are most able to utilise the projected increase in wealth to substantially increase macro scale adaptive capacity (Fig. 2.1). In these regions, increased wealth is projected to have direct effects on the determinants of AC such as infrastructure, technology, and equality. Countries that already show a large AC will also benefit from a growing awareness of global change impacts, but to a lesser degree, as shown in Fig. 2.1. In some cases, a decreasing population trend will negatively affect flexibility, and thus AC. By the end of the century, the differences in AC across Europe converge. Nevertheless, there is still considerable variation, with larger AC in northern regions and lower AC in the Mediterranean countries, as shown in Fig. 2.2. For these countries, the development pathways associated with the scenarios have a large influence. The A1 (global-economic) scenario projects the greatest increase in AC, while the B2 (regional-environmental) scenario is associated with lower adaptive capacity.

Potential impacts

The stratified potential impacts (PIstr) are summarized per ecosystem service indicator, in a similar manner to adaptive capacity (Fig. 2.2). These scatter plots can now be used to (1) compare the impacts on the different ecosystem service indicators, (2) compare the impacts between regions and (3) compare the influence of the SRES storylines. A summary of these scatter plots, where PIstr is classified in five categories, is given in Table 2.4.

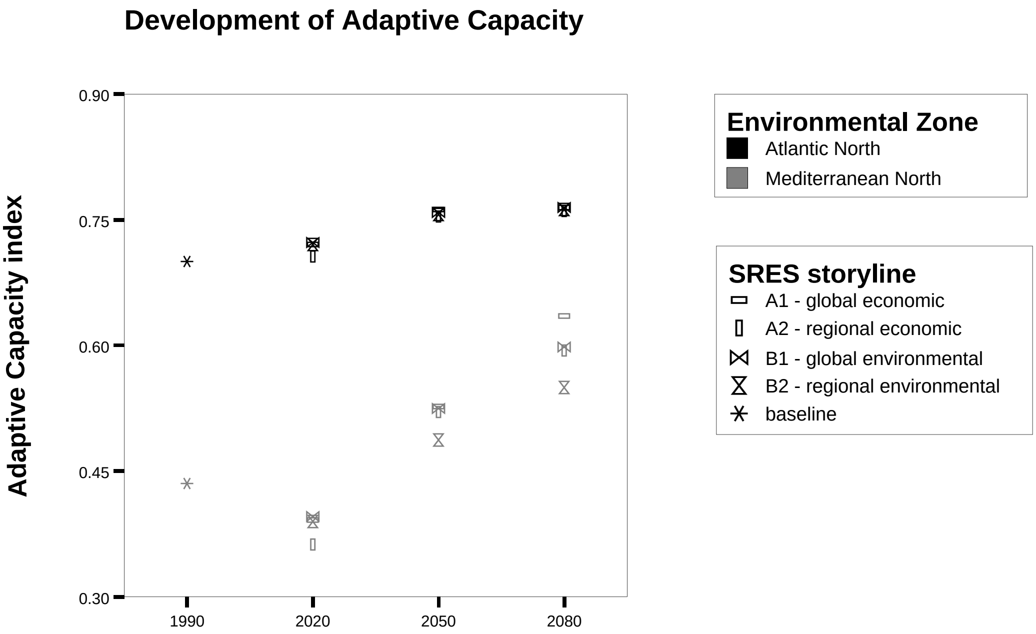

Figure 2.1. Scatter plot showing the development of adaptive capacity (AC) in two Environmental Zones for the four SRES storylines. Although AC increases much more rapidly in the Mediterranean North than in the Atlantic North, toward the end of the 21st century AC is still considerable higher in the Atlantic North.

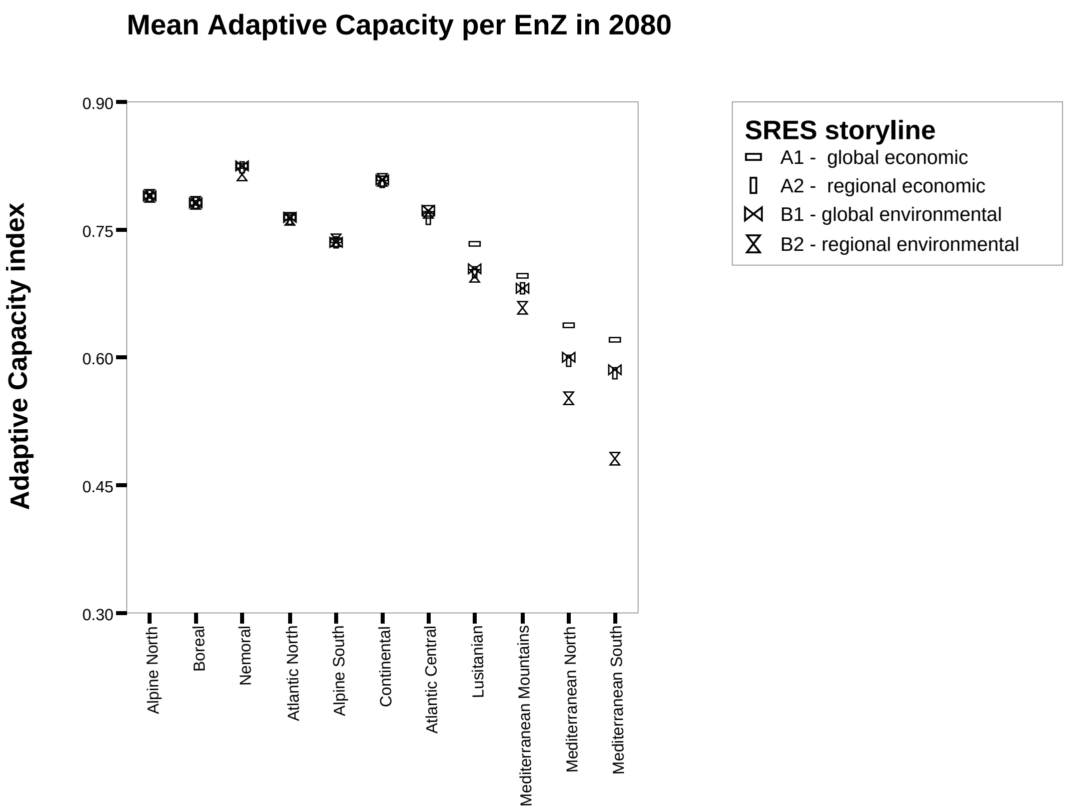

Figure 2.2. Scatter plot of the mean adaptive capacity (AC) per Environmental Zone in 2080 for the four SRES storylines. AC in southern Europe is projected to remain lower than in northern Europe. The influence of future development pathways is greater in southern Europe than in northern Europe.

Table 2.4. Summaries of stratified potential impacts in five categories ranging from very negative to very positive change: -- (PIstr lower than –15), - (PIstr between –15 and –5), 0 (PIstr between –5 and 5), + (PIstr between 5 and 15), ++ (PIstr greater than 15). (a) For the agriculture, forestry and climate regulation sectors PIstr for multiple indicators were averaged. (b) For the nature conservation sector the different indicators were summarized separately because projected impacts show great variability between indicators.

(a)

	Agriculture				**Forestry**				**Climate regulation**				**Count**				
	A1	**A2**	**B1**	**B2**	**A1**	**A2**	**B1**	**B2**	**A1**	**A2**	**B1**	**B2**	**- -**	**-**	**0**	**+**	**++**
Alpine North	-	-	0	0	0	0	0	0	-	-	-	-	0	6	6	0	0
Boreal	-	0	0	0	+	+	+	+	- -	- -	- -	- -	4	1	3	4	0
Nemoral	-	0	0	0	0	0	0	0	0	0	0	0	0	1	11	0	0
Atlantic North	-	-	0	0	0	0	0	0	0	+	+	+	0	2	7	3	0
Alpine South	-	-	-	0	0	0	0	0	+	++	+	++	0	3	5	2	2
Continental	-	-	-	-	0	0	0	0	+	++	++	++	0	4	4	1	3
Atlantic Central	-	- -	-	-	0	0	0	+	0	+	+	+	1	3	4	4	0
Lusitanian	-	-	-	-	0	0	0	0	0	+	++	++	0	4	5	1	2
Med. Mountains	0	0	0	-	0	0	0	0	0	++	+	++	0	1	8	1	2
Med. North	-	-	-	- -	0	0	0	0	+	++	++	++	1	3	4	1	3
Med. South	0	-	-	- -	0	0	0	0	+	+	+	+	1	2	5	4	0
Count - -	0	0	0	2	0	0	0	0	1	1	1	1					
-	9	8	6	4	0	0	0	0	1	1	1	1					
0	2	3	5	5	10	10	10	9	5	1	1	1					
+	0	0	0	0	1	1	1	2	4	4	5	3					
++	0	0	0	0	0	0	0	0	0	4	3	5					

(b)

	Birds				Herptiles				Plants				Trees				Count				
	A1	**A2**	**B1**	**B2**	**A1**	**A2**	**B1**	**B2**	**A1**	**A2**	**B1**	**B2**	**A1**	**A2**	**B1**	**B2**	**- -**	**-**	**0**	**+**	**++**
Alpine North	0	0	-	0	0	-	-	0	0	-	- -	-	-	0	-	0	1	7	8	0	0
Boreal	0	0	0	0	-	-	-	-	0	0	0	-	-	0	0	-	0	7	9	0	0
Nemoral	0	0	0	0	0	0	-	0	0	+	+	+	-	- -	-	-	1	4	8	3	0
Atlantic North	0	0	0	0	0	0	+	0	0	0	0	0	0	+	+	+	0	0	12	4	0
Alpine South	+	+	+	+	0	0	0	0	0	0	0	0	-	-	-	-	0	4	8	4	0
Continental	0	0	0	0	0	-	0	-	-	-	0	-	- -	-	0	-	1	7	8	0	0
Atlantic Central	0	0	0	0	0	0	0	0	0	0	0	0	- -	-	-	-	1	2	12	0	0
Lusitanian	0	0	0	0	-	-	0	0	-	-	0	-	- -	- -	- -	- -	4	5	7	0	0
Med. Mountains	+	+	+	+	0	0	0	+	-	0	-	0	- -	-	- -	-	2	4	5	5	0
Med. North	0	0	0	0	0	0	0	0	0	0	0	-	- -	- -	- -	-	3	2	11	0	0
Med. South	0	0	0	0	0	0	0	0	+	0	0	0	-	-	- -	-	1	3	11	1	0
Count - -	0	0	0	0	0	0	0	0	0	0	1	0	5	3	4	1					
-	0	0	1	0	2	4	3	2	3	3	1	5	5	5	4	8					
0	9	9	8	9	9	7	7	8	7	7	8	5	1	2	2	1					
+	2	2	2	2	0	0	1	1	1	1	1	1		1	1	1					
++	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					

Agriculture

There are strong pressures on agricultural land use under all future scenarios, resulting in declines in agricultural production area. Therefore PIstr for the *farmer livelihood* indicator, based on land availability for agriculture, is negative for most regions of Europe (Fig. 2.3). There appears to be a trend towards more negative PIstr for more southern Environmental Zones (EnZs). Especially the Mediterranean EnZs have very negative PIstr scores. There is a strong influence of the SRES storylines on PIstr. Strong economic development (the A scenarios) is associated with the largest land use changes, which translates into more extreme impacts than the scenarios associated with environmentally oriented development (the B scenarios).

Soil carbon will decrease due to two factors. Firstly, climate change will speed decomposition of soil carbon and secondly, the area under agriculture will decrease. Areas that remain moist under increasing temperatures (e.g. the Boreal EnZ) will lose the most carbon, whereas in areas that become drier, soil carbon loss will be slowed. PIstr remains relatively neutral across all EnZs, except for the Boreal (Fig. 2.3). Furthermore, the influence of the SRES storylines is weak.

Forestry

Climate change will have an overall positive effect on forestry, and therefore on both indicators (*wood production* and *wood supply*), except in the Mediterranean, where higher temperatures and increased droughts increase tree mortality and the risk of forest fires. Furthermore, except for the A2 scenario, all land use scenarios indicate an increase in forest area (Kankaanpäa & Carter, 2004). This will result in positive potential impacts on the ecosystem service indicators (see also Schröter *et al.*, 2004, 2005b). Nevertheless, the PIstr values are relatively neutral, except for the Mediterranean, where PIstr is slightly negative (Fig. 2.4). This is related to increased droughts and fires. The SRES storylines do influence the results slightly. In northern Europe, the global scenarios (A) are most positive, while for southern Europe the environmentally oriented (B) scenarios are the most positive.

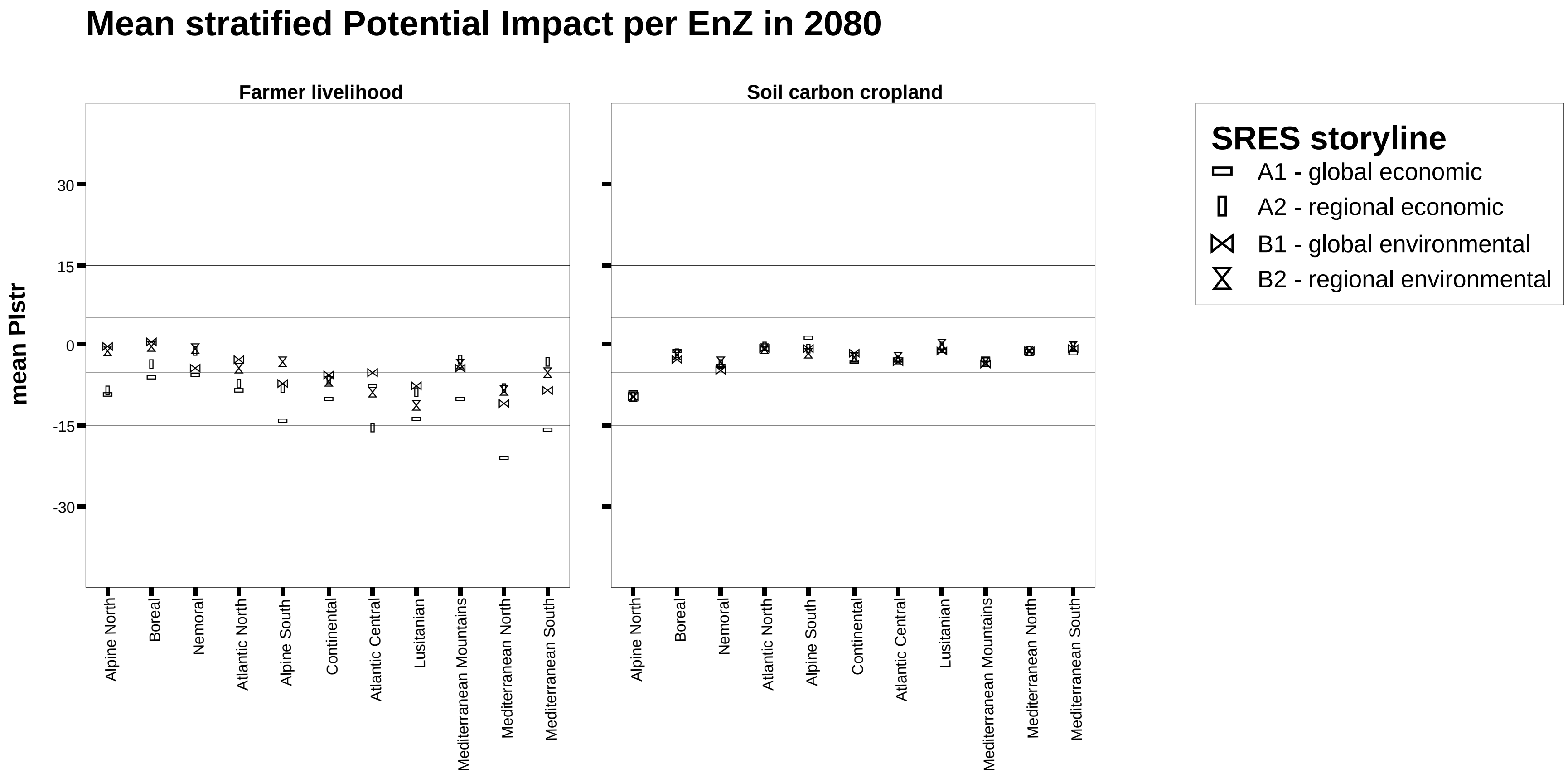

Figure 2.3. Scatter plots of stratified potential impacts (PIstr) for the indicators relevant for the agriculture sector: *farmer livelihood* and *soil carbon*.

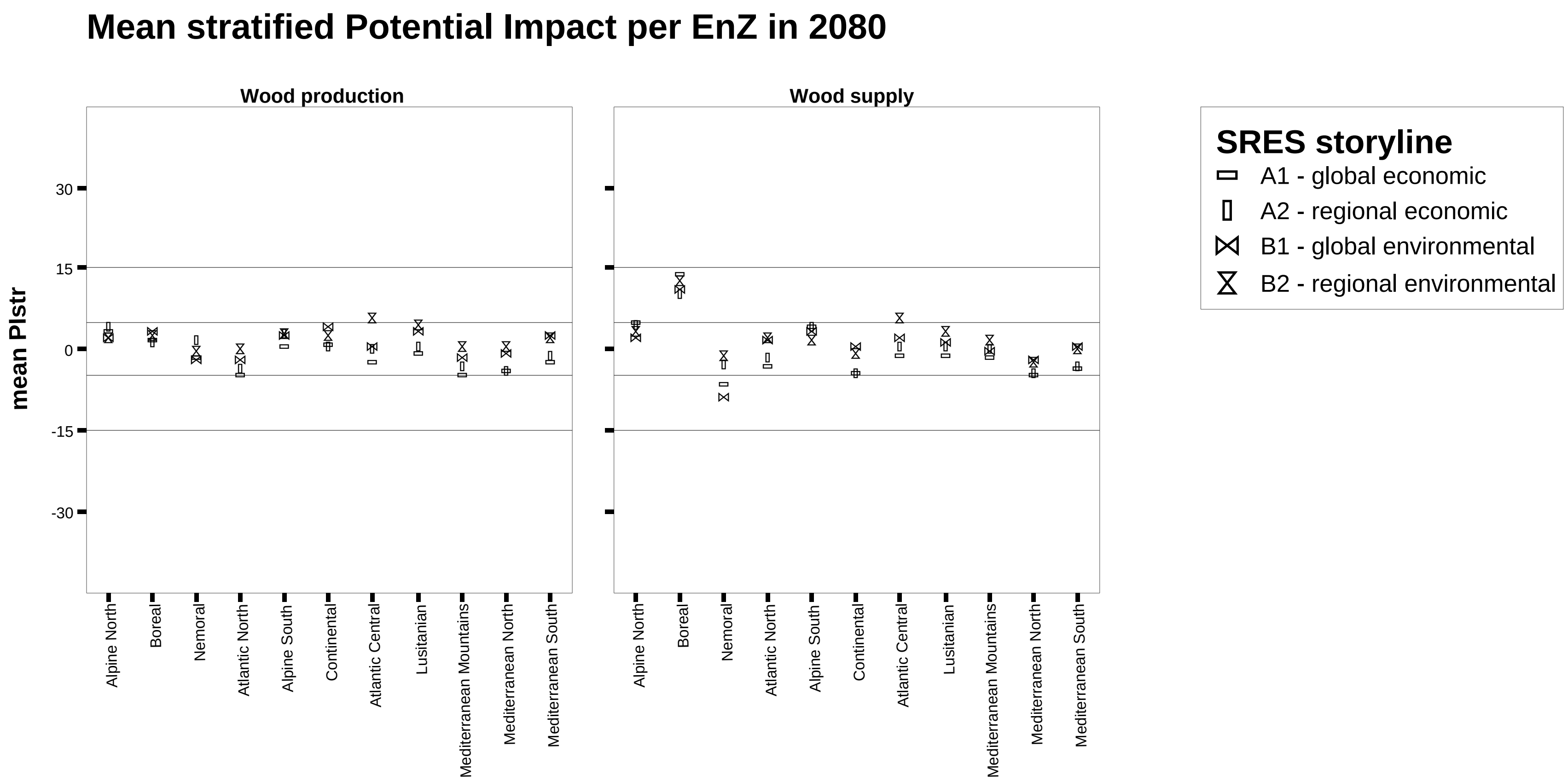

Figure 2.4. Scatter plots of stratified potential impacts (PIstr) for the indicators relevant for the forestry sector: *wood production* and *wood supply*.

Nature conservation

There are large differences in the potential impacts of global change between different groups of species. The distribution ranges of the exothermal herptiles (reptiles and amphibians) are relatively unaffected by a warming climate. Stratified potential impact values are also relatively stable (Fig. 2.5). Also, for bird species, which generally have a wide climatic distribution, the projected impacts are relatively small. There are relatively positive values in the Mediterranean Mountains and the Alpine South. Plant species and tree species on the other hand generally have a narrower climatic envelope. For these groups of species the projected impacts will be the largest. An increase in biodiversity is projected for northern Europe, while southern Europe will see a strong decrease. For a large part, these changes are a direct consequence of the shifts in broad environment, since at the continental scale biodiversity and environment are strongly correlated (see section on stratified potential impacts). PIstr is therefore not as dramatic. Nevertheless, for plant species negative stratified potential impacts are projected for Alpine North, Continental, Lusitanian, Mediterranean Mountains, and Mediterranean North (Fig. 2.5). For the tree species PIstr is negative or very negative in most regions of Europe (Fig. 2.5).

Climate regulation

Climate protection by carbon storage is indicated by net biome production, which can be split in the ecosystem service *net carbon storage*, and the disservice *net carbon emission*. To facilitate interpretation, values for the disservice are multiplied by –1. Negative values are therefore always negative impacts, and vice versa.

Towards the end of the 21st century, the Alpine North and Boreal are projected to become net carbon sources, while the rest of Europe becomes a net carbon sink (Zaehle *et al.*, 2004). The negative stratified values in northern Europe and positive values elsewhere indicate that the increased sink is not just related to the shifting environments, but also to land use change, the age of the forests, and management. The negative PIstr for net carbon emission in Alpine North and Boreal is an effect of the age structure of the forests in these regions. Expansion of forests, projected under all land use scenarios except A2 (contributes to the positive values in the rest of Europe. As can be seen in Fig. 2.6, there is a very strong difference in the values of PIstr depending on the SRES storylines. The B2 scenario is associated with the largest uptake and smallest emission, while for the A1 scenario the smallest uptake and the largest emission is projected.

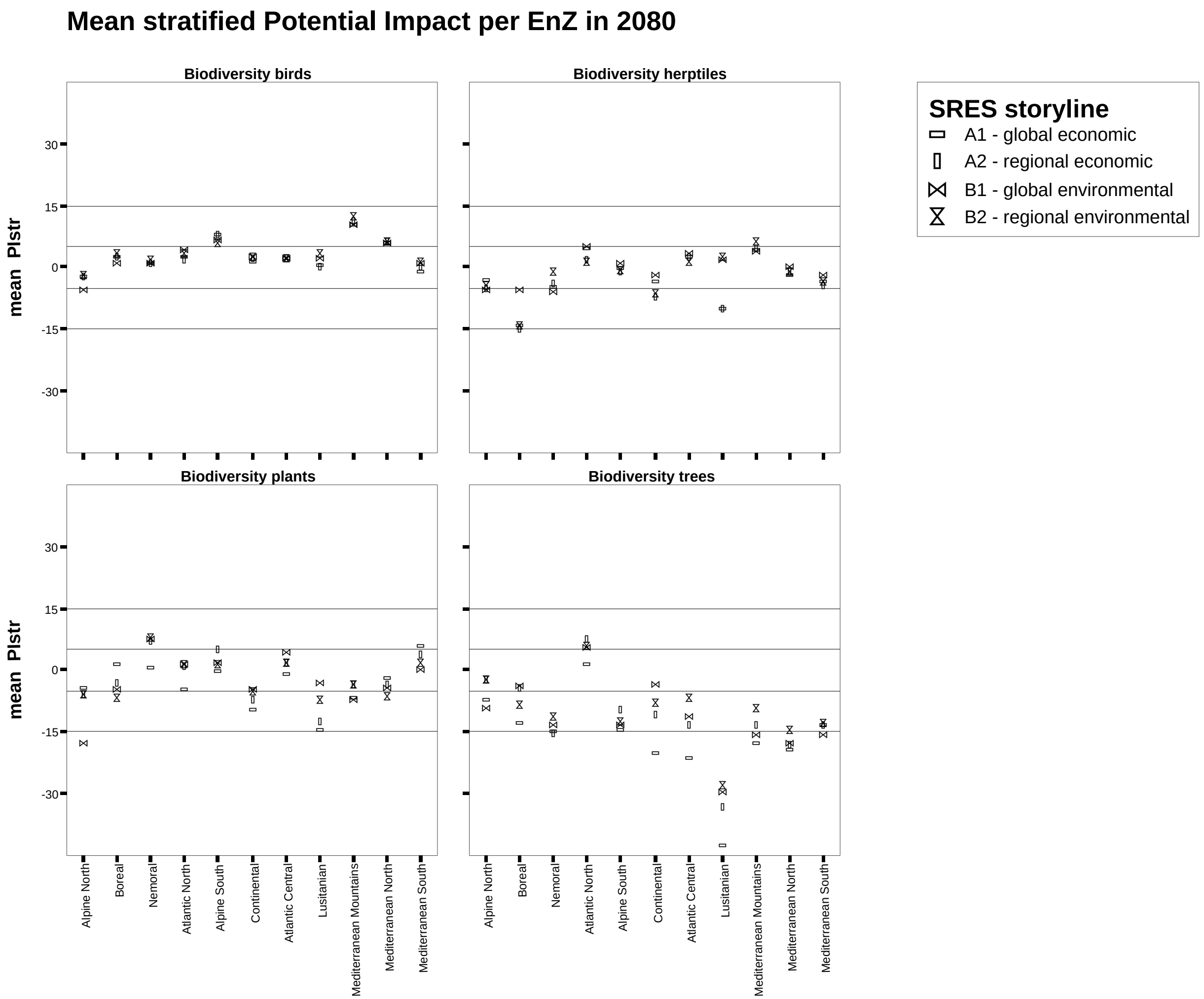

Figure 2.5. Scatter plots of stratified potential impacts (PIstr) for the indicators relevant for the nature conservation sector: *biodiversity of birds, herptiles, plants and trees*.

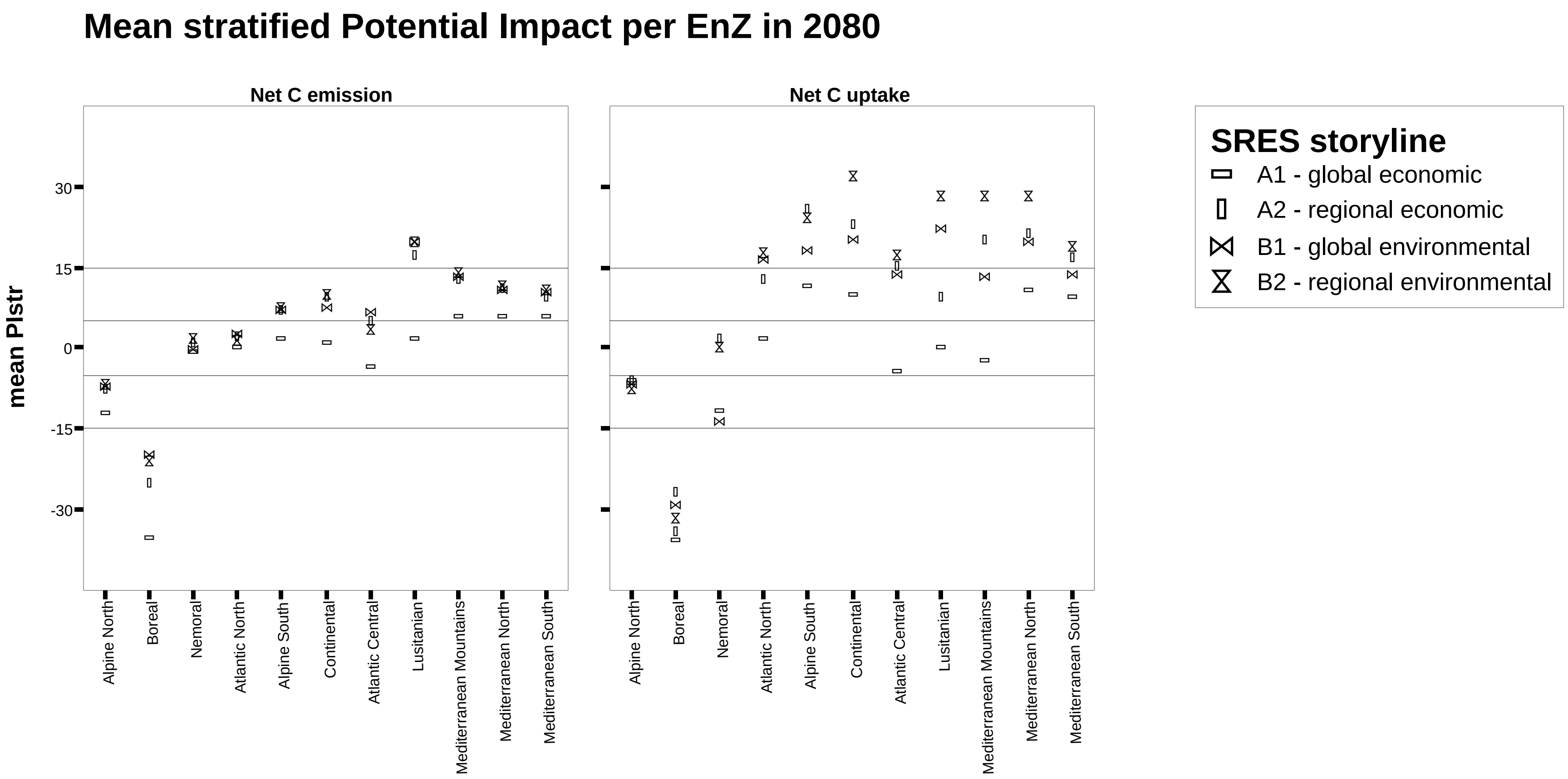

Figure 2.6. Scatter plots of stratified potential impacts (PIstr) for the indicators relevant for the climate regulation sector: *net carbon emission* and *uptake*. Note that values for net carbon emission were multiplied by –1, therefore all posistive values correspond to positive change and *vice versa*.

Discussion and specific findings

adaptive capacity and stratified potential impacts have been quantified and analysed for the principal European Environmental Zones (in Figs 2.3 – 2.6). By combining the findings from these graphs it is possible to make some general statements about the vulnerability of people relying on ecosystem services, without quantifying the relative contributions of PIstr or AC. Firstly, this is done for each of the four sectors. Then, an attempt will be made to identify those regions which are most vulnerable to global change, and those that are less vulnerable, and to assess the influence of the alternative development pathways.

Vulnerability per sector

Agriculture

The agricultural sector is potentially quite vulnerable to global change. While the soil carbon indicators do not give a strong signal in PIstr, in absolute terms they do tend to decrease across Europe. *Farmer livelihood* does give a strong PIstr signal, especially for the southern EnZs, regions that depend more heavily on agriculture than northern Europe. Also, as shown in Fig. 2.2, for southern European EnZs a lower AC is indicated than for northern regions, making them especially vulnerable. In the northern EnZs (Alpine North, Boreal, Nemoral, Atlantic North) the PIstr values are only slightly negative. These regions are also projected to have a high AC under all scenarios (Fig. 2.2). From this we can conclude that northern Europe is less likely to be vulnerable to projected global changes. Conversely, lower AC is indicated for southern EnZs (Lusitanian, Mediterranean zones) and PIstr reaches the very negative values for *farmer livelihood*. Southern Europe, therefore, seems considerably more vulnerable than northern Europe.

The agriculture sector is potentially very vulnerable to both climate and land use change, especially in southern Europe.

Forestry

The ecosystem service indicators for the forestry sector show a relatively neutral response. While changes in management may be required to fully benefit from positive effects of climate change, the increase in adaptive capacity makes the forestry sector in general not very vulnerable. Furthermore, the land use scenarios project an increase in forest in most areas, especially under the B scenarios. In the Mediterranean, forestry will face considerable challenges to cope with increased droughts and risk of forest fires. Here, more intensive management and suitable tree species may be required for sustainable forestry. In the B scenarios these negative impacts are partly counteracted by increased areas available for forestry. Under the A scenario, the stronger increase in AC could help to cope with adverse effects of climate change.

In most regions the forestry sector will benefit from projected changes (increased area and productivity), however the Mediterranean is potentially vulnerable.

Nature conservation

Species distribution patterns are projected to change considerably. The aggregated figures presented here (Fig. 2.5) show that there are large differences in impacts between groups of species. But also, within the groups of species there will be considerable differences between individual species. Furthermore, the results presented here assume full migration of the species, and do not take into account species turnover or species abundance. Nevertheless, these results do show how there are differences in impacts between regions. Alpine North, Boreal, Continental, Lusitanian, Mediterranean North and South appear to face the largest impacts. Relieving these potential impacts through an increase in adaptive capacity will not always be straightforward. However, if AC is also seen as the ability to implement more adequate reserves, ecological networks and protection programmes, perhaps the vulnerability could be reduced. For nature conservation there does however seem to be a strong dichotomy between the development pathways and AC. Here one would expect that the highest AC would be associated with B scenarios, where society has a higher awareness of environmental issues.

There is great variation in projected vulnerability for nature conservation, depending on the species (group), but the wider Mediterranean and Boreal are potentially vulnerable.

Climate regulation

Europe is projected to become a net source of carbon (Zaehle *et al.*, 2004). The greatest source of carbon will be in northern Europe, due to aging forests. There is little that can be done in the sphere of additional carbon storage by forests because forests are already dominant in these regions. The rest of Europe will acts as net carbon sink. In part this is due to a projected increase in the area under forestry (Kankaanpää & Carter, 2004). In addition, climate change will be beneficial for forest productivity in most regions. While sustainable intensive management could help retain stored carbon, there is only limited scope for further carbon storage to counteract emissions.

Vulnerability across Europe

As can be seen clearly from the summarising Table 2.4, projected impacts from global changes vary greatly between sectors. Agriculture face relatively negative prospects, for forestry impacts will be relatively neutral, and for the indicators for climate regulation impacts will be positive in most of Europe. For biodiversity, projected impacts vary greatly between groups of species. Nevertheless, there are also notable differences between regions of Europe.

Table 2.4 shows that Alpine North and the Boreal have the most negative PIstr scores across the sectors. However, because these regions also have the highest projected AC, and in these regions agriculture is less important than in most other parts of Europe, the overall vulnerability will not be as great as it may seem at first.

Relatively neutral impacts are projected for the Nemoral, and the Atlantic North and Central. These regions also have very high AC scores, making these regions less vulnerable than the Continental and Alpine South, regions which face slightly more negative impacts as well as having lower adaptive capacity.

Finally, the Mediterranean region is projected to have the lowest AC, as well as large negative impacts for agriculture and biodiversity (Table 2.4), and to a lesser extent forestry, as discussed previously. The Mediterranean Mountains are less vulnerable than the other Mediterranean Zones.

Influence of development pathways

As Figs 2.2 – 2.6 and Table 2.4 show, in many cases the different development pathways embodied by the SRES storylines will influence the eventual vulnerability. Table 2.4a shows that for the sectors agriculture, forestry and climate regulation, in combination, the A1 scenario has the most negative scores (relatively more negative impacts than positive impacts), A2 and B1 scores are more or less neutral, and the scores for B2 are slightly positive. However, there are differences between sectors, making specific statements about the preferred development pathways a political matter outside the scope of this paper.

In addition, when combining findings about AC and PIstr into conclusions about vulnerability, trade-offs emerge around economic growth in southern Europe. Economic growth is projected to lead to greater technological development, infrastructure, equity, and power, and thus to a higher AC. But at the same time, the SRES scenarios associated with the strongest economic growth (A1, A2) are the scenarios with the largest stratified potential impacts.

More specific statements about vulnerability for southern Europe, therefore, require a better understanding of the relationship between economic growth and AC.

Assumptions and uncertainties

Studies concerned with future developments are necessarily based on a many assumptions, and clouded by uncertainty. It is important to recognize this, making assumptions explicit, and discussing uncertainties. For the present study, three categories of assumptions can be discerned: 1) those associated with the SRES storylines and scenarios 2) those associated with the ecosystem models used to estimate ecosystem service provision, 3) those associated specifically with the vulnerability framework. The first two categories are only briefly discussed here, as they are published elsewhere. Assumptions and uncertainties related to the vulnerability assessment are discussed in more detail.

SRES (Nakicenovic *et al.*, 2000) consists of a comprehensive set of narratives that define the local, regional and global socio-economic driving forces of environmental change (e.g. demography, economy, technology, energy, and agriculture). The storylines provide alternative images of how the future might unfold and can act as an integration tool in the assessment of global change impacts. Because we cannot attach probability to any given storyline, they can help stimulate open discussion. It is however important to realize that all storylines are essentially arbitrary and therefore do not likely depict the most realistic future. The SRES storylines were used to develop internally consistent scenarios for climate and land use change. The four storylines used in ATEAM cover 93% of the range of possible global warming presented by IPCC (Nakicenovic *et al.*, 2000). Uncertainties and assumptions for these datasets are discussed respectively by Mitchell *et al.* (2004) and Rounsevell *et al.* (2005b). For the projections of ecosystem services, uncertainties and assumptions are discussed by Schröter *et al.* (2004 ; 2005b) and in the individual publications of the various models, listed in Table 2.3b.

The stratification adds additional conceptual complexity to the vulnerability framework, but is of importance for allowing comparison across the European environment. The environmental stratification that was used (Chapters 5 and 6; Metzger *et al.*, 2005a) is based on the ATEAM climate change scenarios. Some additional uncertainty is added by the statistical classification, as discussed in Chapters 5 and 6. However one of the more profound assumptions for the present study is the choice of the reference values (ESref). Any reference value that can be applied consistently across different ecosystem services will necessarily be arbitrary. The choice for the highest value of the ecosystem service indicator with the EnS stratum was based on the conceptual notion that potential values of the indicator are restricted by environmental constraints. While this works well for ecosystem indicators that are directly correlated with wider environmental or climatic patterns, it could have significant implications when the maximum value in an outlier within the stratum.

The adaptive capacity indicator framework forms the first scenario-based model of adaptive capacity. It forms a good basis for discussion on the future ability to cope with projected changes, but it is based on several uncertain assumptions. Firstly, the conceptual indicator framework, while based on current scientific understanding of AC, is in part arbitrary, and changes in the choice of indicators could influence the outcome of the indicator. A second major source of uncertainty is the assumption that historical trends in the relation between the 12 indicators of AC and GDP and population, based on time-series data for the last 30 years, will remain the same in the 21st century. Finally, there are uncertainties associated with the fuzzy aggregation of the 12 indicators to a single index. Validation of the adaptive capacity index is difficult, or perhaps impossible, making it difficult to quantify uncertainties.

This last stage of the vulnerability framework, combining the stratified potential impacts and the adaptive capacity indicator into intuitive vulnerability maps also includes some arbitrary choices, especially in the scaling of the adaptive capacity index (Saturation). The relative contribution of AC will probably differ between sectors, across ecosystem services, and perhaps between regions. The present approach gives an initial indication of the combination of AC and PIstr into vulnerability, but for specific issues they should be examined separately, and interpreted in combination with ancillary information and knowledge.

Limitations of the approach

As indicated previously, there is a demand for methods to integrate multidisciplinary assessments and to incorporate measures of adaptive capacity (IPCC, 2001 ; Kasperson & Kasperson, 2001 ; Schröter *et al.*, 2005a). While such methods are aimed at synthesising findings, there is the risk of oversimplification or blurring initial findings with complex meta-analyses and added uncertainties. The present framework attempted to avoid oversimplification by providing separate vulnerability maps for each ecosystem service output. Furthermore, for a better comprehension of vulnerability it is important to analyse not only the vulnerability maps, but also the separate components used to derive the vulnerability map. This approach, with a multitude of maps, has consequences for the ease of interpretation. Scatter plots form an effective tool for summarizing multiple maps, but also require specific software and computer skills. For the ecosystem service indicators modelled by the ATEAM ecosystem models, a separate software shell was developed to facilitate such analyses (Metzger *et al.*, 2004 ; see also the CD-ROM annex).

Any processing of the modelled ecosystem services adds both complexity and uncertainty. In the present approach this processing comprised three parts. (1) The stratification of the ecosystem service maps adds considerable conceptual complexity, but is of importance for allowing comparison across the European environment. Whilst both the environmental stratification that was used (Chapter 5 ; Metzger *et al.*, 2005) and the reference value (ESref) are essentially arbitrary, they can be applied consistently to different ecosystem service indicators and scenarios. (2) The adaptive capacity index meets the needs for a macro-scale indicator, although arguably separate indicators should be developed for different sectors or ecosystem services. (3) The visual combination of the two indices results in an intuitive map, but also includes a bias, especially in the scaling of the adaptive capacity index (Saturation). The relative contribution of AC can be manipulated by changing the scaling. As the approach is applied, more advanced methods of combining stratified potential impact (PIstr) and adaptive capacity (AC) may be developed, i.e. through fuzzy logic or qualitative differential equations. However, a prerequisite for this is the further understanding of how PIstr and AC interact and influence vulnerability.

Concluding remark

The assessment reported here is a first attempt at a Europe-wide quantitative spatial vulnerability assessment, and many uncertainties remain. The results from the present assessment show that vulnerability to global change differs between sectors, regions, and future scenarios, but that southern Europe is especially vulnerable. Further analysis of the outputs can provide the basis for discussion between stakeholders and policymakers about sustainable management of Europe's natural resources.

References

Alcamo J (2002) Introduction to special issue on regional air pollution and climate change in Europe. Environmental Science & Policy 5: 255.

Arnell NW (1999) The effect of climate change on hydrological regimes in Europe: a continental perspective. Global Environmental Change 9: 5-23.

Arnell NW (2003) Effects of IPCC SRES emissions scenarios on river runoff: a global perspective. Hydrology and Earth System Sciences 7: 619-641.

Araújo MB, Williams PH, Fuller R (2002) Dynamics of extinction and the selection of nature reserves. Proceedings of the Royal Society London B 269: 1971-1980.

Coleman K, Jenkinson DS (1996) RothC -26.3- A Model for the turnover of carbon in soil. In: Powlson DS, Smith P, Smith JU (eds) Evaluation of Soil Organic Matter Models Using Existing, Long-Term Datasets. NATO ASI Series I, 38. Springer-Verlag, Heidelberg, Germany, pp 237-246.

Coleman K, Jenkinson DS, Crocker GJ, Grace PR, Klir J, Körschens M, Poulton PR, Richter DD (1997) Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. Geoderma 81: 29-44.

Daily GC (1997) Nature's services. Island Press / Shearwater Books, Washington DC, USA.

Ewert F, Rounsevell MDA, Reginster I, Metzger MJ, Leemans R (2005) Future scenarios of European agricultural land use. I: Estimating changes in crop productivity. Agriculture, Ecosystems and Environment 107: 101-116.

Galloway JN (2001) Acidification of the world: Natural and anthropogenic. Water, Air, and Soil Pollution 130: 17-24.

Geist HJ, Lambin EF (2002) Proximate causes and underlying driving forces of tropical deforestation. Bioscience 52: 143-150.

IMAGE team (2001) The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate change and impacts in the 21st century. National Institute of Public Health and the Environment (RIVM), Bilthoven, The Netherlands.

IPCC (2001) Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

Ittersum MK van, Leffelaar PA, Keulen H van, Kropff MJ, Bastiaans L, Goudriaan J (2003) On approaches and applications of the Wageningen crop models. European Journal of Agronomy 18: 201-234.

Kankaanpää S, Carter TR (2004) Construction of European forest land use scenarios for the 21st century. The Finnish Environment 707. Finnish Environment Institute, Helsinki, Finland.

Karjalainen T, Pussinen A, Liski J, Nabuurs GJ, Erhard M, Eggers T, Sonntag M, Mohren F (2002) An approach towards an estimate of the impact of forest management and climate change on the European forest sector carbon budget: Germany as a case study. Forest Ecology and Management 162: 87-103.

Kasperson JX, Kasperson RE (2001) SEI Risk and Vulnerability, Programme Report 2001-01. Stockholm Environment Institute, Stockholm, Sweden.

Kates RW, Clark WC, Corell R, Hall JM, Jaeger CC, Lowe I, McCarthy JJ, Schellnhuber H-J, Bolin B, Dickson NM, Faucheux S, Gallopin GC, Grübler A, Huntley B, Jäger J, Jodha NS, Kasperson RE, Mabogunje A, Matson PA, Mooney HA, Moore III B, O'Riordan T, Svedin U (2001) Sustainability science. Science 292: 641-642.

Luers AL, Lobell DB, Sklar LS, Addams CL, Matson PA (2003) A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. Global Environmental Change 13: 255-267.

Metzger MJ, Leemans R, Schröter D, Cramer W, the ATEAM consortium (2004) The ATEAM vulnerability mapping tool. Quantitative Approaches in Systems Analysis No. 27, CD-ROM publication, Office C.T. de Wit Graduate School for Production Ecology & Resource Conservation (PE&RC), Wageningen, The Netherlands. [Available on the CD-ROM annex to this thesis]

Metzger MJ, Bunce RGH, Jongman RHG, Mücher CA, Watkins JW (2005) A climatic stratification of the environment of Europe. Global Ecology and Biogeography. In press. [Chapter 5 of this thesis]

Millennium Ecosystem Assessment (2003) Ecosystems and Human Well-being: a framework for assessment. Island Press, Washington DC, USA.

Mitchell TD, Carter TR, Jones PD, Hulme M, New M (2004) A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100). Tyndall Centre Working Paper No. 55. Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK.

Nabuurs GJ, Schelhaas MJ, Pussinen A (2000) Validation of the European Forest Information Scenario Model (EFISCEN) and a projection of Finnish forests. Silva Fennica 34: 167-179.

Nakicenovic N, Alcamo J, Davis G, Vries B de, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, la Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, Rooyen S van, Victor N, Dadi Z (2000) IPCC Special Report on Emission Scenarios (SRES). Cambridge University Press, Cambridge, UK.

Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421: 37-42.

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421: 57-60.

Reid WV, Mooney HA, Cropper A, Capistrano D, Carpenter SR, Chopra K, Dasgupta P, Dietz T, Duraiappah AK, Hassan R, Kasperson R, Leemans R, May RM, McMichael AJ, Pingali P, Samper C, Scholes R, Watson RT, Zakri AH, Shidong Z, Ash NJ, Bennett E, Kumar P, Lee MJ, Raudsepp-Hearne C, Simons H, Thonell J, Zurek NB (2005) Millennium Ecosystem Assessment Synthesis report. Island Press, Washington DC, USA.

Rounsevell MDA, Ewert F, Reginster I, Leemans R, Carter TR (2005a) Future scenarios of European agricultural land use. II: projecting changes in cropland and grassland. Agriculture Ecosystems and Environment 107: 117-135.

Rounsevell MDA, Reginster I, Araújo MB, Carter TR, Dendoncker N, Ewert F, House JI, Kankaanpää S, Leemans R, Metzger MJ, Schmit C, Smith P, Tuck G (2005b) A coherent set of future land use change scenarios for Europe. Agriculture Ecosystems and Environment. In press.

Sabaté S, Gracia CA, Sánchez A (2002) Likely effects of climate change on growth of *Quercus ilex*, *Pinus halepensis*, *Pinus pinaster*, *Pinus sylvestris* and *Fagus sylvatica* forests in the Mediterranean region. Forest Ecology & Management 162: 23-37.

Schröter D, Acosta-Michlik L, Reidsma P, Metzger MJ, Klein RJT (2003) Modelling the Vulnerability of Eco-Social Systems to Global Change: Human Adaptive Capacity to Changes in Ecosystem Service Provision. Paper presented at the 5th Open Meeting of the Human Dimensions of Global Environmental Change Research Community, Montreal, Canada. [http://sedac.ciesin.columbia.edu/openmtg/]

Schröter D, Acosta-Michlik L, Arnell AW, Araújo MB, Badeck F, Bakker M, Bondeau A, Bugmann H, Carter T, Vega-Leinert AC de la, Erhard M, Espiñeira GZ, Ewert F, Friedlingstein P, Fritsch U, Glendining M, Gracia CA, Hickler T, House J, Hulme M, Klein RJT, Krukenberg B, Lavorel S, Leemans R, Lindner M, Liski J, Metzger MJ, Meyer J, Mitchell T, Mohren F, Morales P, Moreno JM, Reginster I, Reidsma P, Rounsevell MDA, Pluimers J, Prentice IC, Pussinen A, Sánchez A, Sabaté S, Sitch S, Smith B, Smith J, Smith P, Sykes MY, Thonicke K, Thuiller W, Tuck G, Werf G van der, Vayreda J, Wattenbach M, Wilson DW, Woodward FI, Zaehle S, Zierl B, Zudin S, Cramer W (2004) The ATEAM final report 2004 – Detailed report related to overall project duration. Advanced Terrestrial Ecosystem Analysis and Modelling, a project funded under the 5th Framework Programme of the European Union. [www.pik-potsdam.de/ateam/]

Schröter D, Polsky C, Patt AG (2005a) Assessing vulnerabilities to the effects of global change: an eight step approach. Mitigation and Adaptation Strategies for Global Change. In press.

Schröter D, Cramer W, Leemans R, Prentice IC, Araújo MB, Arnell NW, Bondeau A, Bugmann H, Carter TR, Garcia CA, Vega-Leinert AC de la, Erhard M, Ewert F, Glendining M, House JI, Kankaanpää S, Klein RJT, Lavorel S, Lindner M, Metzger MJ, Meyer J, Mitchell TD, Reginster I, Rounsevell M, Sabaté S, Sitch S, Smith B, Smith J, Smith P, Sykes MT, Thonicke K, Thuiller W, Tuck G, Zaehle S, Zierl B (2005b) Ecosystem Service Supply and Human Vulnerability to Global Change in Europe. Science. *Pending revisions.*

Sitch S, Smith B, Prentice IC, Arneth A, Bondeau A. Cramer W, Kaplan JO, Levis S, Lucht W, Sykes MT, Thonicke K, Venevsky S (2003) Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Vegetation Model. Global Change Biology 9: 161-185.

Smith JB, Schellnhuber H-J, Qader Mirza M, Fankhauser S, Leemans R, Erda L, Ogallo LA, Pittock BA, Richels R, Rosenzweig C, Safriel U, Tol RSJ, Weyant J, Yohe G (2001) Vulnerability to Climate Change and reasons for concern: A Synthesis. In: McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (eds) Climate Change 2001. Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, UK, pp 913-967.

Smith JU, Bradbury NJ, Addiscott TM (1996) SUNDIAL: A PC-based system for simulating nitrogen dynamics in arable land. Agronomy Journal 88: 38-43.

Steffen W, Tyson P, Jäger J, Matson P, Moore B, Oldfield F, Richardson K, Schelnhuber J, Turner BL, Wasson R (2001) Global change and the earth system: a planet under pressure. IGBP Science 4: 2-32.

Thuiller W (2003) BIOMOD – optimizing predictions of species distributions and projecting potential future shifts under global change. Global Change Biology 9: 1353-1362.

UNEP (2002) GEO-3: Global Environmental Outlook Report 3. UNEP - United Nations Environment Programme.

Venevsky S, Thonicke K, Sitch S, Cramer W (2002) Simulating fire regimes in human-dominated ecosystems: Iberian Peninsula case study. Global Change Biology 8: 984-998.

Vega-Leinert AC de la, Schröter D, Leemans R, Fritsch U, Pluimers J (2005) A stakeholder dialogue on European Vulnerability. Regional Environmental Change. *To appear in ATEAM special issue.*

Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ (eds) (2000) Land Use, Land-Use Change and Forestry. A Special Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

Yohe G, Tol RSJ (2002) Indicators for social and economic coping capacity -- moving toward a working definition of adaptive capacity. Global Environmental Change 12: 25-40

Zaehle S, Bondeau A, Smith P, Sitch S, Schröter D, Erhard M, Cramer W (2004) Europe's terrestrial carbon sink may last until 2050 and then decline. Geophysical Research Abstracts 6: 3808.

Chapter 3

The vulnerability of ecosystem services to land use change

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Agriculture Ecosystems and Environment, in press.

Abstract

Terrestrial ecosystems provide a number of vital services for people and society, such as biodiversity, food, fibre, water resources, carbon sequestration, and recreation. The future capability of ecosystems to provide these services is determined by changes in socio-economic characteristics, land use, biodiversity, atmospheric composition and climate. Most published impact assessments do not address the vulnerability of the human-environment system under such environmental change. They cannot answer important multidisciplinary policy relevant questions such as: which are the main regions or sectors that are vulnerable to global change? How do the vulnerabilities of two regions compare? Which scenario is the least, or most, harmful for a given region or sector?

The *Advanced Terrestrial Ecosystem Analysis and Modelling* project (ATEAM) uses a new approach to ecosystem assessment by integrating the potential impacts in a vulnerability assessment, which can help answer multidisciplinary questions, such as those listed above. This chapter presents the vulnerability assessment of the ATEAM land use scenarios. The 14 land use types, discussed in detail by Rounsevell *et al.* (2005b), can be related to a range of ecosystem services. For instance, forest area is associated with wood production and designated land with outdoor recreation. Directly applying the vulnerability methodology to the land use change scenarios helps in understanding land use change impacts across the European environment. Scatter plots summarizing impacts per principal European Environmental Zone (EnZ) help in interpreting how the impacts of the scenarios differ between ecosystem services and the European environments.

While there is considerable heterogeneity in both the potential impacts of global changes, and the adaptive capacity to cope with these impacts, this assessment shows that southern Europe in particular will be vulnerable to land use change. Projected economic growth increases adaptive capacity, but is also associated with the most negative potential impacts. The potential impacts of more environmentally-oriented developments are smaller, indicating an important role for both policy and society in determining eventual residual impacts.

Introduction

Many aspects of our planet are changing rapidly due to human activities and these changes are expected to accelerate during the next decades (IPCC, 2001abc). For example, forest area in the tropics is declining (Geist & Lambin, 2002), many species are threatened with extinction (Thomas *et al.*, 2004), and rising atmospheric carbon dioxide results in global warming (IPCC, 2001abc). Many of these changes will have an immediate and strong effect on agriculture, forestry, biodiversity, human health and well-being, and on amenities such as traditional landscapes (Watson *et al.*, 2000 ; UNEP, 2002). Furthermore, a growing global population, with increasing per capita consumption of food and energy, are expected to continue emitting pollutants to the atmosphere, resulting in continued nitrogen deposition and eutrophication of environments (Galloway, 2001 ; Alcamo, 2002). In the face of these changes, it is important to integrate and extend current operational systems for monitoring and reporting on environmental and social conditions (cf Kates *et al.*, 2001). Over the last decades many people have become increasingly aware of these environmental changes, such that they are now commonly recognized as 'global change' (Steffen *et al.*, 2001). Many research projects and several environmental assessments are currently addressing these concerns at all relevant scales, frequently in multidisciplinary collaborations. However, integrating this wealth of information across disciplines remains a considerable challenge (Millennium Ecosystem Assessment, 2003).

This paper aims to quantify global-change concerns, focusing specifically on changes associated with scenarios of land use change, by defining and estimating vulnerabilities. Both the vulnerability concept, discussed in chapter 1 and by Metzger and Schröter (submitted) and the land use change scenarios (Rounsevell *et al.*, 2005a ; Ewert *et al.*, 2005 ; Kankaanpää & Carter, 2004 ; Rounsevell *et al.*, 2005b) described in this Chapter were developed as part of the *Advanced Terrestrial Ecosystem Analysis and Modelling* project (ATEAM). Detailed information about the project can be found on its website (http://www.pik-potsdam.de/ateam).

Amongst the many aspects of global change, land use change has been highlighted as a key human-induced affect on ecosystems (Turner *et al.*, 1997 ; Lambin *et al.*, 2001). Land use has been changing since people first began to manage their environment, but the changes in Europe over the past 50 years have been especially important. An increasingly urbanized society has led to the major development of settlements, improved technology to a changing role for agriculture and new aspirations have lead to land being used for recreation and leisure. Such land use change directly influences the provision ecosystem services (e.g. provision of food and timber, climate regulation, nutrient cycling, and cultural identity) (Daily, 1997 ; Millennium Ecosystem Assessment, 2003 ; Reid *et al.*, 2005). In the vulnerability concept used in this chapter, the sustainable supply of ecosystem services is used as a measure of human well-being under the influence of global change threats, as indicated by the Millennium Ecosystem Assessment (2003). This is similar to the approach used by Luers *et al.*, (2003) in looking at the vulnerability of Mexican farmers to decreasing wheat yields arising from climate damage and market fluctuations.

The *Synthesis* chapter (Smith *et al.*, 2001) of the *Intergovernmental Panel on Climate Change* (IPCC) *Third Assessment Report* (TAR) recognized the limitations of traditional impact assessments, where a few climate-change scenarios are used to assess the response of a system at a future time. Smith *et al.* (2001) challenged the scientific community to move towards more transient assessments that are a function of shifting environmental parameters (including climate) and socio-economic trends, and explicitly include the ability to innovate and adapt to the resulting changes. A step towards meeting this challenge is their definition of 'vulnerability':

Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes (IPCC TAR).

Although this definition addresses climate change only, it already includes susceptibility, which is a function of exposure, sensitivity, and adaptive capacity. The vulnerability concept developed for ATEAM is a further elaboration of this definition and was developed especially to integrate results from a broad range of models and scenarios. Projections of changing supply of different ecosystem services and scenario-based changes in adaptive capacity are integrated into vulnerability maps for different socio-economic sectors (agriculture, forestry, water management, energy, and nature conservation) (Schröter *et al.*, 2004 ; 2005b). These vulnerability maps provide a means of making comparisons between ecosystem services, sectors, scenarios and regions to tackle questions such as:

- Which regions are most vulnerable to global change ?
- How do the vulnerabilities of two regions compare ?
- Which sectors are the most vulnerable in a certain region ?
- Which scenario is the least harmful for a sector ?

The term vulnerability was thus defined in such a way to include both the traditional elements of an impact assessment (i.e. potential impacts of a system to exposures), and adaptive capacity to cope with the potential impacts of global change (Turner *et al.*, 2003 ; Schröter *et al.*, 2005a).

The following sections first summarize the concepts of the spatially explicit and quantitative framework that was developed for a vulnerability assessment for Europe. It is explained how various land use changes were coupled to changes in ecosystem service provision, and the findings are discussed per principal European Environmental Zone.

Methods

The terminology developed by the IPCC forms a suitable starting point for explaining the different elements of the vulnerability assessment presented here. This section first defines and explains the various elements of the vulnerability concept, including exposure, potential impacts and adaptive capacity, and how these elements are combined to form vulnerability maps. Then the derivation of five ecosystem service indicators from the ATEAM land use scenarios (Rounsevell *et al.*, 2005b) is explained. Finally, the vulnerability assessment of these scenarios is presented, based on ecosystem service indicators.

The concept of vulnerability

As a starting point for the ATEAM vulnerability concept, the IPCC definitions of vulnerability to climate change, and related terms such as exposure, sensitivity, and adaptive capacity, were broadened in order to consider not only climate change, but also other global changes such as land use change (Schröter *et al.*, 2004 ; 2005b). Table 3.1 lists the definitions of some fundamental terms used in this chapter and gives an example of how these terms could relate to the agriculture sector. From these definitions the following generic functions are constructed, describing the vulnerability of a sector relying on a particular ecosystem service at a particular location (e.g. grid cell) under a certain scenario and at a certain point in time. Vulnerability is a function of exposure, sensitivity and adaptive capacity (equation 1). Potential impacts are a function of exposure and sensitivity (equation 2). Therefore, vulnerability is a function of potential impacts and adaptive capacity (equation 3):

$$V(es, x, s, t) = f\left(E(es, x, s, t), S(es, x, s, t), AC(es, x, s, t) \right) \quad (1)$$

$$PI(es, x, s, t) = f\left(E(es, x, s, t), S(es, x, s, t) \right) \quad (2)$$

$$V(es, x, s, t) = f\left(PI(es, x, s, t), AC(es, x, s, t) \right) \quad (3)$$

where V = vulnerability, E = exposure, S = sensitivity, AC = adaptive capacity and PI = potential impact, es = ecosystem service, x = a grid cell, s = a scenario, t = a time slice

Table 3.1. Definitions of important terminology related to vulnerability, with an example for the agriculture sector. IPCC TAR = Intergovernmental Panel on Climate Change Third Assessment Report (IPCC 2001).

Term		ATEAM definitions based on IPCC TAR	Part of the assessment	Agriculture example
Exposure	**(E)**	The nature and degree to which ecosystems are exposed to environmental change.	Scenarios	Land abandonment, increased climatic stress, decreases in demand
Sensitivity	**(S)**	The degree to which a human-environment system is affected, either adversely or beneficially, by environmental change.	Ecosystem Models	Agricultural ecosystems, communities and landscapes are affected by environmental change
Adaptation	**(A)**	Adjustment in natural or human systems to a new or changing environment.		Changes in local management, changes crops
Potential Impact	**(PI)**	All impacts that may occur given projected environmental change, without considering planned adaptation.		Decreases in agricultural land
Adaptive Capacity	**(AC)**	The potential to implement planned adaptation measures.	Vulnerability Assessment	Capacity to implement better agricultural management and technologies
Vulnerability	**(V)**	The degree to which an ecosystem service is sensitive to global change plus the degree to which the sector that relies on this service is unable to adapt to the changes.		Increased probability of production losses through losses of agricultural area combined with inability to switch to save cash and quality crops
Planned Adaptation	**(PA)**	The result of a deliberate policy decision based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain or achieve a desired state.	The future will tell.	Better agricultural management and technologies
Residual Impact	**(RI)**	The impacts of global change that would occur after considering planned adaptation.		Land abandonment, intensification

These simple conceptual functions describe how the different elements of vulnerability are related to each other. Nevertheless, they are not immediately operational for converting maps of ecosystem services into vulnerability maps. The following sections illustrate how vulnerability is quantified and mapped in the present study, using one ecosystem service indicator, *farmer livelihood*, as an example.

Exposure, sensitivity and potential impacts

The IPCC projections of the main global change drivers, based on the *Special Report on Emissions Scenarios* (SRES) (Nakicenovic *et al.*, 2000) were used to represent exposure. SRES consists of a comprehensive set of narratives that define the local, regional and global socio-economic driving forces of environmental change (e.g. demography, economy, technology, energy, and agriculture). The SRES storylines were structured in four major 'families' labelled A1, A2, B1 and B2, each of which emphasizes a largely different set of social and economic development pathways, organized along two axes. The vertical axis represents a distinction between more economically (A) and more environmentally and equity (B) orientated futures. The horizontal axis represents the range between more globalization (1) and more regionally-oriented developments (2). Rounsevell *et al*, (2005b) give a summary of the main trends in the ATEAM land use scenarios.

Scenarios were developed for atmospheric carbon dioxide concentration, climate (Mitchell *et al.*, 2004), socio-economic variables, and land use (Rounsevell *et al.*, 2005b). These scenarios are internally consistent, and considered explicitly the global context of European land use (i.e. import and export of agricultural goods). The IMAGE implementation (IMAGE team, 2001) of these scenarios was used to define the global context (trade, socio-economic trends, demography, global emissions and atmospheric concentrations, climate change levels). The high-resolution (10 arcmin x 10 arcmin, approximately 16 km x 16 km in Europe) land use change scenarios used in this vulnerability assessment were derived from an interpretation of the SRES storylines. The vulnerability assessment spans a wide range of plausible futures for three time slices (1990-2020, 2020-2050, 2050-2080).

In ATEAM, ecosystem service provision was estimated by ecosystem models as a function of ecosystem sensitivity and global change exposure. In this study ecosystem service provision was directly linked to the land use scenarios, as discussed below. The resulting range of outputs for each ecosystem service indicator enabled the differentiation of regions that are impacted under most scenarios, regions that are impacted under specific scenarios, and regions that are not impacted under any scenario.

The example maps in this chapter are restricted to the ecosystem service indicator *farmer livelihood* (Fig. CP4.1). For this ecosystem service indicator, the vulnerability approach is illustrated with maps for one scenario, the A1 scenario, which assumes continued globalisation with a focus on economic growth. The analysis of multiple scenarios is discussed in the section *Analysis of the results*.

Stratified potential impacts

The estimation of potential impacts is undertaken at the regional scale, emphasizing the differences across the European environment. Simply comparing changes in ecosystem services across Europe provides only a limited analysis of regional differences because ecosystem services are highly correlated with their environments. Some environments have high values for particular ecosystem services, whereas other regions have lower values. For instance, Spain has high biodiversity (5048 vascular plant species (WCMC, 1992)), but low grain yields (2.7 t ha^{-1} for 1998-2000 average (Ekboir, 2002)), whereas The Netherlands has a far lower biodiversity (1477 vascular plant species (Meijden van der *et al.*, 1996)), but a high grain yield (8.1 t ha^{-1} for 1998-2000 average (Ekboir, 2002)). While human decisions influence regional land use more directly than broad environmental conditions, at a European scale land use is in part a function of environment (Chapter 5 ; Thuiller *et al.*, 2004). This is illustrated in Fig. 3.1, where agricultural land use, derived from Eurostat NewCronos agricultural statistics, is summarized for four Environmental Zones (see Fig. CP1.2, 1990). Agriculture is almost absent in Alpine North. Grasslands and arable land dominate the Atlantic regions, with more grassland than arable land in Atlantic North and *vice versa* in Atlantic Central. Permanent crops cover 39% of Mediterranean South. Because of the relationship between broad environment and land use, absolute differences in land use percentages are not good measures for comparing regional impacts between different European environments. Looking at relative changes would overcome this problem (e.g. –40% arable land in Mediterranean South *versus* +8% in the Boreal), but also has a serious limitation: the same relative change can occur in very different situations. Table 3.2 illustrates how a relative change of –20% can represent very different impacts, both between and within environments. Therefore comparisons of relative changes in single grid cells must be interpreted with great care.

Table 3.2 Example of changes in the *farmer livelihood* indicator (i.e. percentage of grid cell with agricultural land use) in four grid cells and two different environments between two time slices (t and t+1). Absolute change is not a suitable indicator for potential impact because it is correlated to environmental conditions. Relative change is also not a good measure because the same value (here 20%) can occur represent very different impacts.

	environment 1				environment 2			
	grid cell A		grid cell B		grid cell C		grid cell D	
	t	t+1	t	t+1	t	t+1	t	t+1
Farmer livelihood	30	24	10	8	80	64	50	40
Absolute change		**–6**		**–2**		**–16**		**–10**
Relative change (%)		**–20**		**–20**		**–20**		**–20**

Table 3.3. The environmental conditions for high *farmer livelihood* decreases over time in environment 1, and increases over time in environment 2. When changes are stratified by their environment, comparison of potential impacts in their specific environmental context is possible. The 'Stratified potential impact' is the 'Value in a grid cell' divided by the 'Highest ecosystem service value' in a specific environmental stratum at a specific time slice (see text).

	environment 1				environment 2			
	grid cell A		grid cell B		grid cell C		grid cell D	
	t	t+1	t	t+1	t	t+1	t	t+1
Farmer livelihood	30	24	10	8	80	64	50	40
Highest ecosystem service value (ESref)	30	27	30	27	80	88	80	8.8
Stratified ecosystem service provision (ESstr)	1.0	0.9	0.3	0.3	1.0	0.7	0.6	0.5
Stratified potential impact index (PIstr)		**–0.1**		**0.0**		**–0.3**		**–0.1**

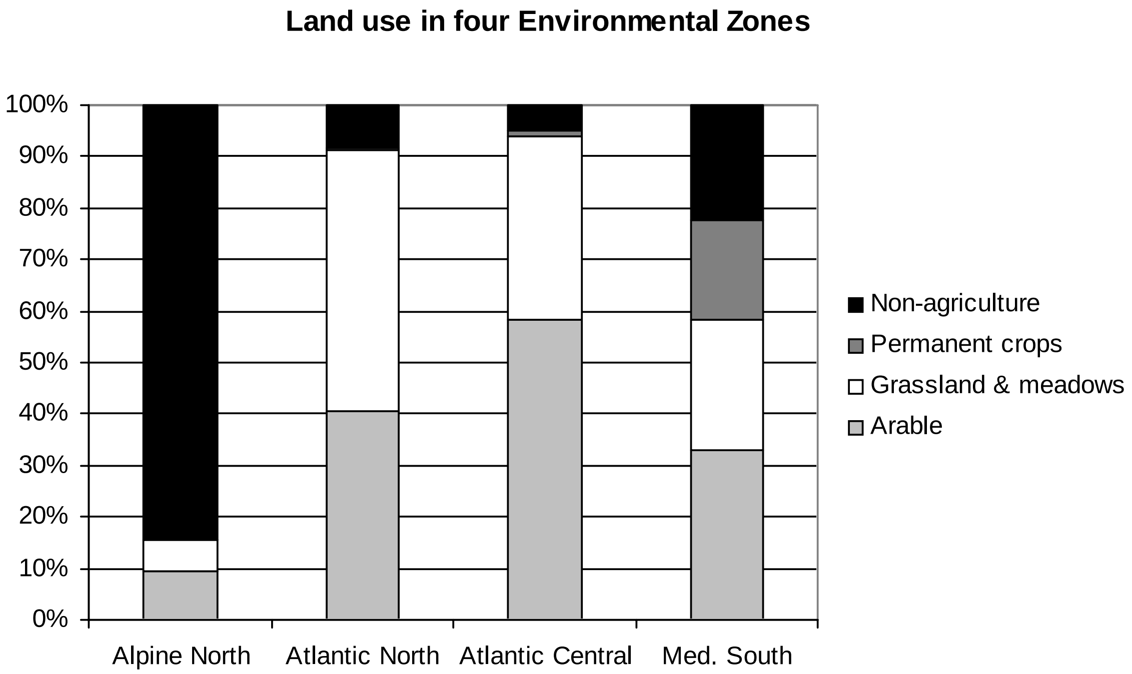

Figure 3.1. Proportions of agricultural land uses in four Environmental Zones (Chapter 5) based on Eurostat NewCronos agricultural statistics.

For a meaningful comparison of grid cells across Europe it is necessary to place potential impacts in their regional environmental context, i.e. in an environmental envelope, or stratum, that is suited as a reference for the values in an individual grid cell. Because environments will alter under global change, consistent environmental strata must be determined for each time slice. We used the recently developed *Environmental Stratification of Europe* (EnS) to stratify the modelled potential impacts (Chapter 5 ; Metzger *et al.*, 2005a). The EnS was created by statistical clustering of selected climate and topographical variables into 84 strata. For each stratum a discriminant function was calculated for the variables available from the climate change scenarios. With these functions the 84 climate classes were mapped for the different GCMs, scenarios and time slices, resulting in 48 maps of shifted climate classes (Chapter 6). Maps of the EnS, for baseline and the HadCM3-A1 scenario are mapped in Fig. CP1.2 for aggregated Environmental Zones (EnZs). With these maps, all modelled potential impacts on ecosystems can be placed consistently in their environmental context.

Within an environmental stratum, ecosystem service indicators can be expressed relative to a reference value. While any reference value is inevitably arbitrary, in order to make comparisons it is important that the stratification is performed consistently. The reference value used in this assessment is the highest ecosystem service value achieved in an environmental stratum. This measure can be compared to the concept of potential yield, defined by growth limiting environmental factors (Ittersum van *et al.*, 2003). For a grid cell in a given EnS stratum, the fraction of the modelled ecosystem service provision relative to the highest achieved ecosystem service value in the region (ESref) is calculated, giving a unitless stratified value of the ecosystem service provision (ESstr) with a 0–1 range for the ecosystem service in the grid cell (cf equation 4). Thus ESref is unique for each ecosystem service indicator, time slice, scenario, and EnS stratum.

$$ESstr_{(es,\, x,\, s,\, t)} = ES_{(es,\, x,\, s,\, t)} / ESref_{(es,\, ens,\, s,\, t)} \quad (4)$$

where ESstr = stratified ecosystem service provision, ES = ecosystem service provision and ESref = highest achieved ecosystem service value, es = ecosystem service, x = a grid cell, s = a scenario, t = a time slice and ens = an environmental stratum

In this way a map is created in which potential impacts on ecosystem services are stratified by their environment and expressed relative to a reference value (Fig. CP4.2). Because the environment changes over time, both the reference value and the environmental stratification are determined for each time slice. As shown in Fig. CP4.2, the stratified ecosystem service provision map shows more regional detail than the original non-stratified map. This is the regional detail required to compare potential impacts across regions (see also Table 3.3). The change in stratified ecosystem service provision compared to baseline conditions shows how changes in ecosystem services affect a given location (see also Table 3.3). Regions where ecosystem service supply increases relative to the environment have a positive change in potential impact and *vice versa* (see Fig. CP5.1). This change in ESstr (equation 5) gives a measure of stratified potential impact (PIstr), which is used to estimate vulnerability (see below).

$$PIstr_{(es,\, x,\, s,\, t)} = ESstr_{(es,\, x,\, s,\, t)} - ESstr_{(es,\, x,\, s,\, baseline)} \quad (5)$$

where PIstr = stratified potential impact, ESstr = stratified ecosystem service provision, es = ecosystem service, x = a grid cell, s = a scenario, t = a time slice, baseline = 1990.

Adaptive capacity index

Adaptation in general is understood as an adjustment in natural or human systems in response to actual or expected environmental change, which moderates harm or exploits beneficial opportunities. Here, adaptive capacity reflects the potential to implement planned adaptation measures and is, therefore, concerned with deliberate human attempts to adapt to or cope with change. ‘Autonomous adaptation’ by contrast, does not constitute a conscious response (e.g. spontaneous ecological changes). The concept of adaptive capacity was introduced in the *IPCC TAR* (IPCC, 2001a), according to which the factors that determine adaptive capacity to climate change include economic wealth, technology and infrastructure, information, knowledge and skills, institutions, equity and social capital. Thus far, only one study has made an attempt at quantifying adaptive capacity based on observations of past hazard events (Yohe & Tol, 2002). For the vulnerability assessment framework, present-day and future estimates of adaptive capacity were sought that would be quantitative, spatially explicit, and based on, as well as consistent with, the SRES storylines described above. A generic index was developed of macro-scale adaptive capacity. Four steps were followed to derive the adaptive capacity indices:

1. Development of a socio-economic framework using indicator-based approach.
2. Estimation of future values of the indicators using regression models.
3. Aggregation of the estimated values of the indicators using fuzzy models.
4. Validity tests of the fuzzy models using uncertainty and sensitivity analyses.

Based on literature review, six determinants were selected as a basis for building a framework of adaptive capacity (Schröter *et al.*, 2003 ; Klein *et al.*, in prep.). Two socio-economic indicators were used to represent each determinant of adaptive capacity. The framework thus includes 12 indicators, as indicated in Fig. 3.2. Time-series data for each of the 12 indicators was collected for regional administrative units of the countries in the project. Regression techniques were applied to the data to estimate the future values of the indicators for different time slices (2000, 2020, 2050 and 2080) and for each SRES storyline. Fuzzy logic was used to aggregate the estimated values of the indicators to generate the adaptive capacity index. This technique offers flexible means to assess the numerical values of the indicators through the linguistic values and soft thresholds of the membership functions (Cornelissen *et al.*, 2001 ; Eierdanz *et al.*, submitted to *Mitigation and Adaptation Strategies for Global Change*). This flexibility is relevant for evaluating concepts such as adaptive capacity, which as yet does not have an objective yardstick to assess its relative magnitude. The validity of the fuzzy models, in particular with respect to the thresholds and gradients of the membership functions, was tested using uncertainty analysis.

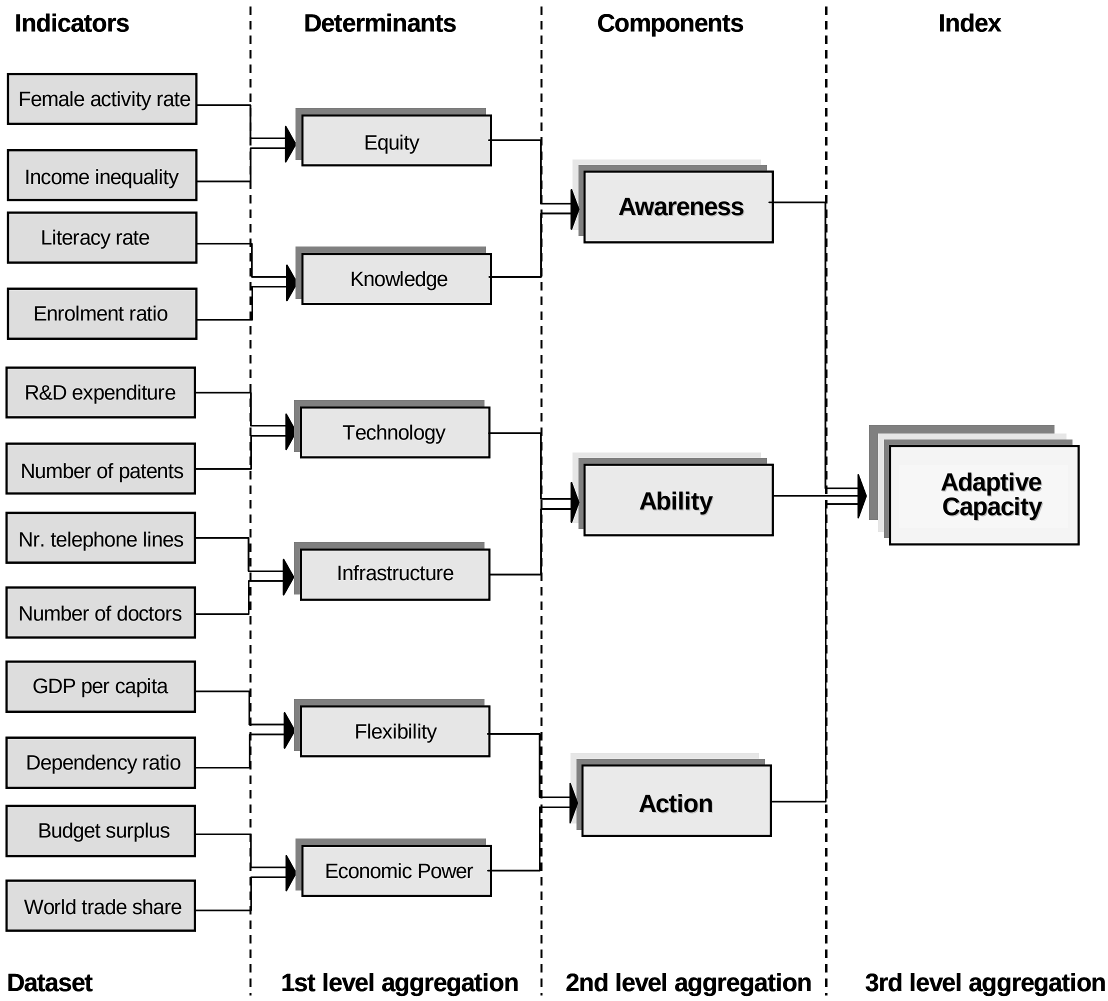

Figure 3.2. Indicator framework used to develop the adaptive capacity model.

An illustrative example of the developments of the adaptive capacity index over time is given in Fig. CP3.1. Different regions in Europe show different adaptive capacities. For baseline conditions, adaptive capacity is lowest in southern European countries, which score relatively low values for the AC indicators listed in Fig. 3.2. Under the global economic (A1) scenario, the adaptive capacity index becomes higher across Europe, since global markets lead to positive development for most of the AC indicators (see Fig. 2.1). In the southern European countries some of the AC indicators increase rapidly under this scenario, e.g. in Spain *female activity rate* is projected to rise from 35% to 60%, and in Italy there is a projected rise in the *number of doctors* from approximately 6 to 11 per 1000 inhabitants. Nevertheless, the adaptive capacity of the southern European countries remains lower than for northern European countries (see Fig. 2.2).

Vulnerability maps

The different elements of the vulnerability function (equation 3) have now been quantified, as summarized in Fig. CP6. The last step, the combination of the stratified potential impact (PIstr) and the adaptive capacity index (AC), is however the most difficult step, especially when taking into account the limited empirical basis of the adaptive capacity index. It was therefore decided to create a visual combination of PIstr and AC without quantifying a specific relationship between them. For further analytical purposes the constituents of vulnerability, the changes in potential impact and the adaptive capacity index, are viewed separately.

Trends in vulnerability follow the trend in PIstr: when ecosystem service supply decreases, humans relying on that particular ecosystem service become more vulnerable in that region. Alternatively, vulnerability decreases when ecosystem service supply increases. Adaptive capacity lowers vulnerability. In regions with similar changes in potential impact, a region with a high AC will be less vulnerable than a region with a low AC. The PIstr determines the Hue, ranging from red (decreasing ecosystem service provision, PIstr = –1, highest negative potential impact) through yellow (no change in ecosystem service provision, PIstr = 0, no potential impact) to green (increase in ecosystem service provision, PIstr = 1, highest positive potential impact). Note that it is possible that while the modelled potential impact remains unchanged, the stratified potential impact increases or decreases because of changes in the highest value of ecosystem service supply in the environmental class (ESref). Thus, when the environment changes, this is reflected in the potential impact.

Adaptive capacity determines colour saturation and ranges from 50% to 100% depending on the level of the AC. When the PIstr becomes more negative, a higher AC will lower the vulnerability, therefore a higher AC value has a lower saturation, resulting in a less bright shade of red. Alternatively, when ecosystem service supply increases (PIstr > 0), a higher AC value has a higher saturation, resulting in a brighter shade of green. Conversely, in areas of negative impact, low AC gives brighter red, whereas in areas of positive impacts low AC gives less bright green. Fig. CP5.2 shows the vulnerability maps and the legend for *farmer livelihood* under the A1 scenario for the HadCM3 GCM. Under this scenario *farmer livelihood* decreases in extensive agricultural areas. The role of AC becomes apparent in rural France and Spain, where France is less vulnerable than Spain due to a higher AC, i.e. a supposed higher ability of the French agricultural sector to react to these potential impacts.

Land use services

The ATEAM land use change scenarios (Rounsevell *et al.*, 2005b) were developed with the aim of supporting the types of vulnerability assessments presented here. Within ATEAM, different ecosystem models were run with these scenarios to give insights into the potential impacts of global change for different European sectors. The ecosystem service indicators calculated by these models were analysed with the vulnerability methodology described in the previous sections. This section describes how ecosystem service indicators can also be derived directly from the land use change scenarios. Results from the analysis of such indicators help in understanding the vulnerability of ecosystem services to land use change.

The ATEAM land use scenarios, described in detail by Rounsevell *et al.* (2005b), are based on an interpretation of the SRES storylines (Nakicenovic *et al.*, 2000) for Europe using models and/or approaches that were specific to each land use type; urban (Reginster & Rounsevell, submitted) ; cropland, grassland and bio-energy crops (Ewert *et al.*, 2005 ; Rounsevell, *et al.*, 2005a) ; and forests (Kankaanpää & Carter, 2004). The approach also identified evolving patterns of protected areas based either on conservation or recreation goals (Reginster *et al.*, in prep.), as well as land areas without viable economic activities (termed 'surplus land'). The scenario methodology first estimated changes in land use quantities at aggregate spatial levels (e.g. countries or regions) from an interpretation of the European land use change drivers that were consistent with the SRES storyline descriptions. These land use quantities were then distributed geographically (to the 10 arcminute ATEAM grid) using scenario-specific, spatial allocation rules to reflect alternative societal behaviour and policy goals. The final set of land use change scenarios provided a range of coherent visions of the future integrating alternative socio-economic development pathways with the impacts of climate change.

The provision of many ecosystem services relies directly on land use. For instance, food production relies on agricultural land use, wood production on forestry, and outdoor recreation on attractive landscapes. Table 3.4 shows how the different land use types from the ATEAM scenarios were aggregated to create indicators for five ecosystem services. These indicators are described briefly below.

Table 3.4. The relationship between ATEAM land use types (Rounsevell *et al.*, 2005b) and five ecosystem service indicators.

	Ecosystem service indicators				
Land use	**Regional food production**	**Fibre production**	**Energy production**	**Farmer livelihood**	**Outdoor recreation**
Urban					
Cropland	✓	✓		✓	
Grassland	✓			✓	✓
Forest		✓			✓
Bioenergy crops			✓	✓	
Protected cropland	✓	✓		✓	✓
Protected grassland	✓			✓	✓
Others					✓
Surplus					✓

Fibre, energy and regional food production

These provisioning ecosystem services are most easily associated with types of land use. Food production can be directly related to agricultural land use, fibre production to forestry and cropland and energy production to the area used for bio-energy crops, as indicated in Table 3.4. The actual ecosystem service provision, in crop yield or timber increment, greatly depends on biophysical growing conditions. However, as discussed above, in order to compare ecosystem services across Europe, differences caused by inherently different environments were removed using the stratification. Therefore, for the vulnerability concept used here, the land use types form appropriate indicators for ecosystem service provision.

In the land use change scenarios, reductions in agricultural land are an effect of intensification of production in optimal regions. Hence, total food availability will not decrease. Nevertheless, decreasing regional food production does have consequences for consumers, because regional food products are associated with variation as well as traditional foods. Furthermore, regionally produced food is frequently associated with high quality and safety standards. A more limited choice of foods, mass-produced in optimal locations will be seen as negative impacts by parts of society.

Farmer livelihood

The change in agricultural areas was used as a proxy for the impacts of global change on the well-being of farmers, termed the farmer livelihood. The number of farmers (and workers) employed in agriculture is partly a function of the area of agricultural land, although cultural and economic factors also play a role. For example, economies of scale seem largely responsible for the current, observed trend in increasing farm sizes and thus, fewer farms and farmers. Any reduction in the area of agricultural land use resulting from pressures on the agricultural sector will, therefore, lead to a reduction in the number of farmers. For this reason, changing land use areas were thought to be an appropriate measure of the impact of global change on farmers. The land use scenarios presented here (Rounsevell *et al.*, 2005b) that did not have reductions in agricultural areas (e.g. the B2 scenario) were based on an assumption of extensification (encouraged through market support or rural development mechanisms) and thus, maintenance of the *status quo* with respect to farmer numbers.

Outdoor recreation

Natural or traditional landscapes are suitable for outdoor recreation (e.g. hiking, cycling, hunting, and camping). These landscapes are not easily linked to the land use types in the ATEAM scenarios. For simplicity all non-urban land uses except conventional cropland (including bio-energy crops) were deemed suitable for outdoor recreation. Conventional cropland was not deemed suitable because it is mostly inaccessible for recreational purposes. Furthermore, the scenic value of cropland is considered to be lower than for grassland. Designated cropland was considered to include more traditional landscapes (e.g. small scale mosaic landscapes) and was therefore included in the indicator.

Analysis of the results

The vulnerability maps give an intuitive overview for an ecosystem service indicator for one scenario and for one time slice. It is however difficult to analyse the effects of the four scenarios on the five ecosystem service indicators for a multitude of vulnerability maps. Furthermore, because the legend of these maps is two-dimensional (adaptive capacity and stratified potential impact), it is difficult to analyse the cause of the vulnerability. A comprehensive way of analysing the vulnerability maps is to look at AC and PIstr separately. Scatter plots can be used to summarize impacts for multiple scenarios in one plot. In the following sections AC and PIstr are summarized in scatter plots, showing heterogeneity in AC and PIstr across Europe, as well as differences in PIstr between ecosystem service indicators.

Results and discussion

Adaptive capacity

The capacity of different countries and regions in Europe to cope with the effects of global change is projected to increase in the coming century. Regression analysis of time-series data for the AC indicators (Fig. 3.2) indicated a positive relation between GDP and the indicators. Therefore, the assumed economic growth is expected to have a positive influence on AC. While gross domestic product (GDP) growth is projected for all countries, countries that currently have a lower adaptive capacity (e.g. the Mediterranean countries) are most able to utilize the projected increase in wealth to substantially increase macro scale adaptive capacity (Fig. 2.1). In these regions, increased wealth is projected to have direct effects on the determinants of AC, as illustrated above for the indicators *female activity rate* and *number of doctors*. Countries that already show a large AC will also benefit form a growing awareness of global change impacts, but to a lesser degree, as shown in Fig. 2.1. In some cases, a decreasing population trend will negatively affect flexibility, and thus AC. By the end of the century, the differences in AC across Europe converge. Nevertheless, there is still considerable variation, with larger AC in northern regions and lower AC in the Mediterranean countries, as shown in Fig. 2.2. For these countries, the development pathways associated with the scenarios have a large influence. The A1 (global-economic) scenario projects the greatest increase in AC, while the B2 (regional-environmental) scenario is associated with lower adaptive capacity.

Potential impacts

The stratified potential impacts (PIstr) are summarized per ecosystem service indicator, in a similar manner to AC (Fig. 3.3). In order to further facilitate interpretation, PIstr is classified into five categories, based on the full range of values. The classes range from very positive impacts (PIstr > 0.15), positive impacts (PIstr between 0.05 and 0.15), neutral (PIstr between 0.05 and –0.05), negative (PIstr between –0.05 and –0.15), and very negative (PIstr < –0.15). The scatter plots in Fig. 3.3 can now be used to (1) compare the impacts on the different ecosystem service indicators, (2) compare the impacts between regions and (3) compare the influence of the SRES scenarios. The conclusions of these three analyses are used to draw more general conclusions about the vulnerability of the ecosystem service indicators to land use change.

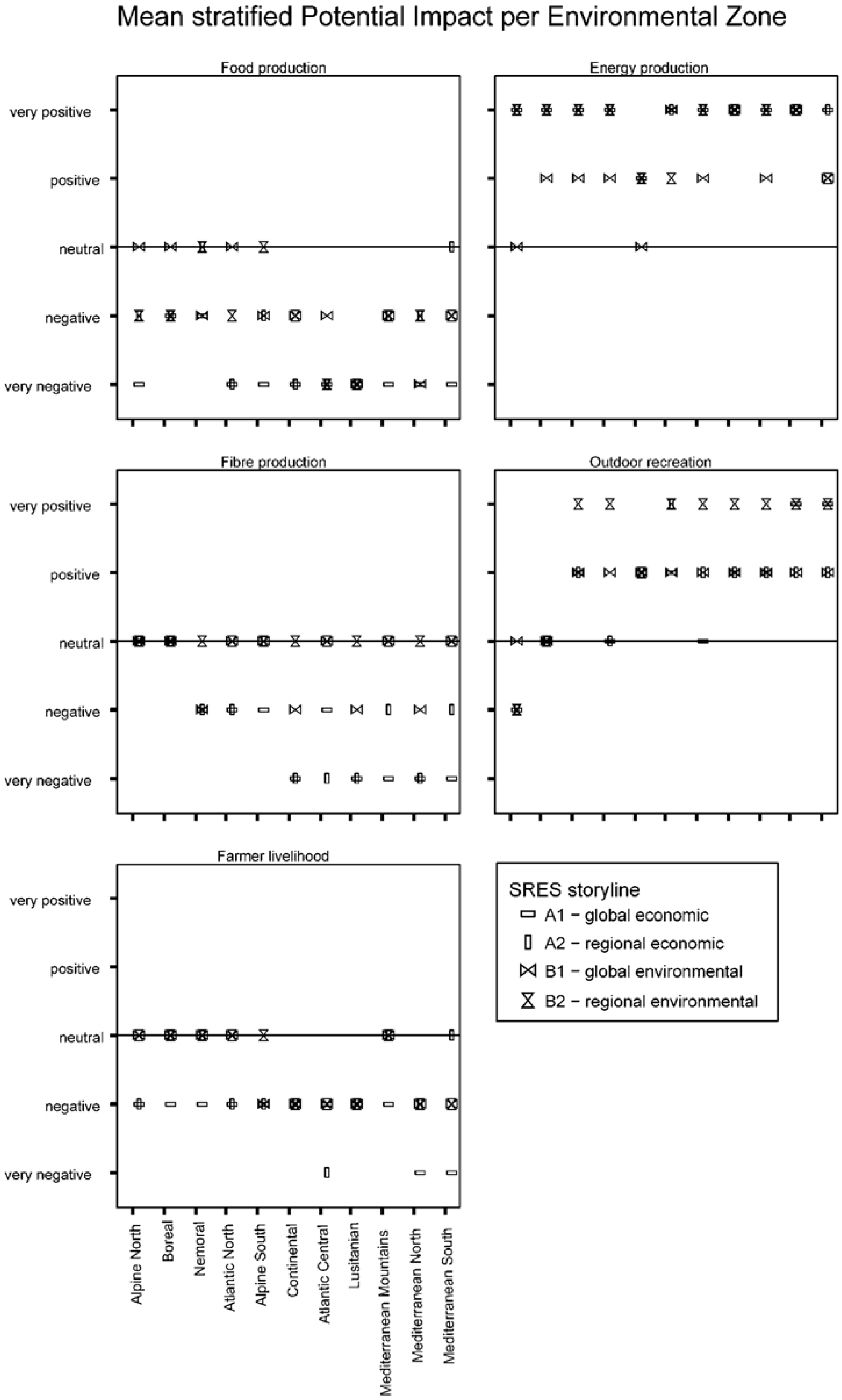

Figure 3.12. Five scatter plots showing stratified potential impact (PIstr) of ecosystem service indicators, in five categories, per Environmental Zone for the SRES storylines. These plots illustrate the differences between ecosystem services, the variability across the European environment, and the influence of the SRES storylines.

The stratified potential impacts (PIstr) for the ecosystem service indicators presented here are a direct result of the ATEAM land use change scenarios (Rounsevell *et al.*, 2005b). Ecosystem services relying on land use types that are projected to emerge, or expand, in the 21st century have a positive PIstr. This is the case for *energy production*, a function of the bio-fuel land use, and *outdoor recreation*, which is a function of the increasing land use type *forest* and the new type *surplus land*. The other ecosystem service indicators rely heavily on the decreasing agricultural land use types, and therefore largely show negative potential impacts. Across the whole of Europe, the *regional food production* indicator had the most negative PIstr scores.

Fig. 3.3 shows that PIstr for Energy production and Outdoor recreation is positive or very positive for most regions in Europe. For the other ecosystem service indicators there is heterogeneity in the impacts between different regions of Europe. There appears to be a trend towards more negative PIstr for more southern Environmental Zones (EnZs). Especially the Mediterranean EnZs have many 'very negative' PIstr scores.

There is a strong influence of the SRES scenarios on PIstr. Nevertheless, the direction of PIstr, positive or negative, is not influenced by the scenarios. Strong economic development (the A scenarios), is associated with the largest land use changes (Rounsevell *et al.*, 2005b), which translates into more extreme impacts than the scenarios associated with environmentally focused development (the B scenarios). Mediterranean North and South both face very negative impacts for *regional food production*, *farmer livelihood*, and *fibre production* under the A1 scenario. In Fig. 3.3, there does not appear to be a clear signal differentiating the global and regional scenarios (1 and 2, respectively). This is an artefact of the aggregation into five classes. In the original data a differentiation can be found, with lower impacts for the regionally-oriented scenarios. However, the difference is far smaller than the differentiation between the A and B scenarios, and not distinct enough to appear in the aggregation.

Vulnerability

Adaptive capacity and potential impact are quantified and analyzed for the principal European Environmental Zones (in Fig. 2.1 and Fig. 3.3, respectively). By combining the findings from these graphs it is possible to make some general statements about the vulnerability of the ecosystem services to land use change, without quantifying the relative contribution of PI and AC.

The northern EnZs (Alpine North, Boreal, Nemoral, Atlantic North) are projected to have a high AC under all SRES scenarios (Fig. 2.1). Furthermore, PIstr reaches the 'very negative' category in just 3 of the 48 possible combinations of EnZ (4), scenario (4) and ecosystem service (3, which have negative impacts) (see also Fig. 2.2). From this we can conclude that northern Europe is less likely to be vulnerable to projected land use changes. The ecosystem service indicators that rely on agricultural land uses do show a negative PIstr, but the high level of AC compensates for this in the final vulnerability. Conversely, southern EnZs (Lusitanian, Mediterranean zones) have a lower AC than the northern regions (Fig. 2.1) and PIstr reaches the 'very negative' category in 16 of the 48 possible combinations. Southern Europe, therefore, seems considerably more vulnerable than northern Europe, especially for ecosystem services relying on agriculture.

Combining findings about AC and PIstr into conclusions about vulnerability shows a strong tension around economic growth in southern Europe. Economic growth is projected to lead to greater technological development, infrastructure, equity, and power, and thus to a higher AC. But at the same time, the SRES scenarios associated with the strongest economic growth (A1, A2) are the scenarios with the largest land use changes and the most negative PIstr: 13 times the 'very negative' PIstr category in 24 possible combinations of EnZ (4), scenario (2) and ecosystem service (3). For the B1 and B2 environmentally-oriented scenarios, PIstr reaches the 'very negative' category just 3 times in 24 possible combinations. More specific statements about vulnerability for southern Europe, therefore, require a better understanding of the relationship between economic growth and AC.

Land use scenarios in vulnerability assessment

Scenarios are useful for exploring uncertainties in vulnerability assessment on a regional basis, e.g. some regions show equal vulnerability to all scenarios, whilst other regions show different responses. This is an indicator for where we can be more, or less, uncertain about the future. Furthermore, it helps in indicating how society and policy can have an important role to play in future development pathways.

Vulnerability assessment provides a means of adding value to land use change scenarios by translating land use maps into information that is more directly relevant to people. This includes an examination of the vulnerability implications of land use change for different groups of people. For example the simple indicators used here were able to address the vulnerability of the suppliers of agricultural products (i.e. farmers and the communities that depend on farming) through the *farmer livelihood* indicator as well as the consumers of those products through the *regional food quality* indicators. Such analyses add richness to scenario development exercises that go beyond simple representations of land use on maps. They do more than just explain why land use change occurs, by also identifying why these changes are important. Furthermore, possible conflicts between vulnerable groups detected (e.g. between farmers and tax-payers). This is the type of information for example that can be of interest to policymakers and society at large, and can help influence future development pathways. By extension, more detailed land use scenarios provide the opportunity to explore more detailed indicators of vulnerability provided the scenarios are constructed to a consistent framework.

Assumptions and uncertainties

Studies concerned with future developments are necessarily based on a many assumptions, and clouded by uncertainty. It is important to recognize this, making assumptions explicit, and discussing uncertainties. For the present study, three categories of assumptions can be discerned: (1) those associated with the SRES storylines, (2) those associated with the various scenarios based on these storylines, and (3) those associated specifically with the vulnerability framework. The first two categories are only briefly discussed here, as they are discussed by Nakicenovic *et al.* (2000). Assumptions and uncertainties related to the vulnerability assessment are discussed in more detail.

SRES (Nakicenovic *et al.*, 2000) consists of a comprehensive set of narratives that define the local, regional and global socio-economic driving forces of environmental change (e.g. demography, economy, technology, energy, and agriculture). The storylines provide alternative images of how the future might unfold and can act as an integration tool in the assessment of global change impacts. Because we cannot attach probability to any given storyline, they can help stimulate open discussion. It is however important to realize that all storylines are essentially arbitrary and therefore do not likely depict the most realistic future. The SRES storylines were used to develop internally consistent scenarios for climate and land use change. The four storylines used in ATEAM cover 93% of the range of possible global warming presented by IPCC (Nakicenovic *et al.*, 2000). Uncertainties and assumptions for these datasets are discussed respectively by Mitchell *et al.* (2004) and Rounsevell *et al.* (2005b).

For the present study, simplistic assumptions were made in order to link the ATEAM land use scenarios to different ecosystem services (cf Table 3.4). These ecosystem service indicators are not very specific, and groups relying on these ecosystem services are heterogeneous. For instance, for mountaineers and hunters the *outdoor recreation* indicator could be of interest. However, the mountaineer will not be interested in expansion of forest area, which will affect the indicator. Other indicators can lead to similar interpretation problems. It is therefore important to communicate to stakeholders what the indicators entail.

The stratification adds additional conceptual complexity to the vulnerability framework, but is of importance for allowing comparison across the European environment. The environmental stratification that was used (Chapters 5 and 6) is based on the ATEAM climate change scenarios. Some additional uncertainty is added by the statistical classification, as discussed in Chapters 5 and 6. However one of the more profound assumptions for the present study is the choice of the reference values (ESref). Any reference value that can be applied consistently across different ecosystem services will necessarily be arbitrary. The choice for the highest value of the ecosystem service indicator with the EnS stratum was based on the conceptual notion that potential values of the indicator are restricted by environmental constraints. While this works well for ecosystem indicators that are directly correlated with wider environmental or climatic patterns, it could have significant implications when the maximum value in an outlier within the stratum. However, for the land use indicators in the present study, the potential range of values for the indicators is restricted by the fact that grid cells cannot be covered by more than 100%.

The adaptive capacity indicator framework forms the first scenario-based model of adaptive capacity. It forms a good basis for discussion on the future ability to cope with projected changes, but it is based on several uncertain assumptions. Firstly, the conceptual indicator framework (Fig. 3.2), while based on current scientific understanding of AC, is in part arbitrary, and changes in the choice of indicators could influence the outcome of the indicator. A second major source of uncertainty is the assumption that historical trends in the relation between the 12 indicators of AC and GDP and population, based on time-series data for the last 30 years, will remain the same in the 21st century. Finally, there are uncertainties associated with the fuzzy aggregation of the 12 indicators to a single index. Validation of the adaptive capacity index is difficult, or perhaps impossible, making it difficult to quantify uncertainties.

This last stage of the vulnerability framework, combining the stratified potential impacts and the adaptive capacity indicator into intuitive vulnerability maps also includes some arbitrary choices, especially in the scaling of the adaptive capacity index (Saturation). The relative contribution of AC will probably differ between sectors, across ecosystem services, and perhaps between regions. The present approach gives an initial indication of the combination of AC and PIstr into vulnerability, but for specific issues they should be examined separately, and interpreted in combination with ancillary information and knowledge.

Limitations in the approach

As indicated previously, there is a demand for methods to integrate multidisciplinary assessments and to incorporate measures of adaptive capacity (IPCC, 2001a ; Kasperson & Kasperson, 2001 ; Schröter *et al.*, 2005a). While such methods are aimed at synthesizing findings, there is the risk of oversimplification or blurring initial findings with complex meta-analyses and added uncertainties. The present framework attempted to avoid oversimplification by providing separate vulnerability maps for each ecosystem service output. Furthermore, for a better comprehension of vulnerability it is important to analyse not only the vulnerability maps, but also the separate components used to derive the vulnerability map. This approach, with a multitude of maps, has consequences for the ease of interpretation. Scatter plots form an effective tool for summarizing multiple maps, but also require specific software and computer skills. For the ecosystem service indicators modelled by the ATEAM ecosystem models, a separate software shell was developed to facilitate such analyses (Metzger *et al.*, 2004 ; available on the CD-ROM annex).

Any processing of the modelled ecosystem services adds both complexity and uncertainty, as discussed in the previous section. In the present approach such additional complexity is added in (1) the stratification process, (2) in the adaptive capacity index, and (3) the visual combination of the two indices results into vulnerability maps. As the approach is applied, more advanced methods of combining stratified potential impact (PIstr) and adaptive capacity (AC) may be developed, i.e. through fuzzy logic or qualitative differential equations. However, a prerequisite for this is the further understanding of how PIstr and AC interact and influence vulnerability.

It is important to realize that the land use change scenarios were developed to provide European results relevant for analysis at the European scale. As a consequence, regional heterogeneity in land use was ignored, and the number of land use types that could be distinguished was limited. As a result, more specific ecosystem services, and especially those related to biodiversity and nature conservation, cannot be assessed. In addition, the agricultural land use scenarios appear to lack sensitivity to climate change. This is partly because the socio-economic drivers are more important than climate drivers within the land use change model, but also because of the effects of scale. At the regional scale, there are winners and losers (in terms of crop yield changes in response to climate change), but these tend to cancel each other out when aggregated to the whole of Europe (Ewert *et al.*, 2005). Thus, the results suggest that at the European scale, crop productivity is not sensitive to climate change, whereas at the regional scale it could be very sensitive to climate change depending on the region in question (Rounsevell *et al.*, 2005a). The models for the other land use types were not at all sensitive to climate change. For ecosystem services that are especially sensitive to climate, a vulnerability assessment based on only land use change does not suffice, and more specific attention should also be paid to the potential impacts to climate change.

Possible future developments and improvements

The present approach was developed for the ATEAM project, but could equally well be used in other assessments. In Chapter 5 Metzger *et al.* show how biomes can be used to stratify ecosystem service indicators from the global model IMAGE (IMAGE team, 2001). There are two limitations to applying the complete vulnerability framework to other modelling studies: both a quantitative stratification and some measure of adaptive capacity need to be available. For European assessments such (e.g. EURURALIS, 2004) this should not pose too much of a problem, as the datasets used in the presented study could be used. For other regions, such datasets may need to be developed. Application of the vulnerability framework to global change impacts in the arctic region are currently under discussion.

Both the modelled changes in ecosystem service provision and the adaptive capacity index form top-down projections which ignore regional heterogeneity. In a flood-prone area in Germany it recently has been shown that ‘perceived adaptive capacity’ is a major determinant of whether people will take adaptation measures or not (Grothmann & Reusswig, 2005). It seems that more place based studies could better take account of the individual nature of vulnerability. One possible consistent method of analysis would be to assess impacts on detailed random sample areas (cf Bunce & Harvey, 1987). For such sample areas it would also be possible to develop more detailed, regional land use change scenarios, by combining high-quality regional ancillary data sources, as discussed in Chapter 6 of this thesis for the impacts of shifting environments in four sample regions. Such regional scenarios can provide the detail required for analysing impacts on biodiversity or nature conservation. By constraining these scenarios with top-down European scenarios, European and global socio-economic trends can be taken into account.

Conclusions

Land use change will have a large influence on important ecosystem services in Europe. Vulnerability to land use change differs across European regions and between ecosystem services. While projected land use changes can be negative for one sector, other sectors could benefit. The vulnerability concept used in this chapter allows different regions of Europe to be compared with respect to their vulnerability to changes in land use related ecosystem services for alternative scenarios. There are differences in potential impact for the different scenarios in most regions, with the most notable distinctions caused by differences in economic *versus* environmentally-oriented development. These differences are most profound in southern Europe, where very negative impacts are foreseen for sectors relying on agricultural ecosystem services under the economically-oriented development pathways associated with open markets. While the ability to cope with such negative impacts increases with growing economic development, southern Europe is projected to have a considerably lower adaptive capacity than northern Europe. From this, it can be concluded that the agricultural sectors in particular in southern European will be most vulnerable to projected land use changes in Europe. However, the differences in both potential impacts and adaptive capacity between the four scenarios, show that the vulnerably of southern Europe is strongly influenced by different development pathways. Society and policy will therefore play an important role in determining the eventual, residual impacts.

References

Alcamo J (2002) Introduction to special issue on regional air pollution and climate change in Europe. Environmental Science & Policy 5: 255.

Bunce RGH, Harvey DR (1987) A methodology for the identification of land areas with potential for energy and industrial agricultural production. In: Grassi G, Delmon B, Molle J-F, Zibetta H (eds) Biomass for energy and industry. Elsevier Applied Science, London, UK, pp 1272-1278.

Cornelissen AMG, Berg J van den, Koops WJ, Grossman M, Udo HMJ (2001) Assessment of the Contribution of Sustainability Indicators to Sustainable Development: A Novel Approach Using Fuzzy Set Theory. Agriculture Ecosystems and Environment 86: 173-185.

Daily GC (1997) Nature's services. Island Press / Shearwater Books, Washington DC, USA.

Ekboir J (ed) (2002) CIMMYT 2000-2001 World Wheat Overview and Outlook: Developing No-Till Packages for Small-Scale Farmers. CIMMYT, Mexico.

EURURALIS (2004) A scenario study on Europe’s Rural Areas to support policy discussion. WUR/RIVM CDrom publication. Wageningen, Bilthoven, The Netherlands.

Ewert F, Rounsevell MDA, Reginster I, Metzger MJ, Leemans R (2005) Future scenarios of European agricultural land use. I: Estimating changes in crop productivity. Agriculture, Ecosystems and Environment 107: 101-116.

Galloway JN (2001) Acidification of the world: Natural and anthropogenic. Water, Air, and Soil Pollution 130: 17-24.

Geist HJ, Lambin EF (2002) Proximate causes and underlying driving forces of tropical deforestation. Bioscience 52: 143-150.

Grothmann T, Reusswig F (2005) People at risk of flooding: why some residents take precautionary action while others do not. Natural Hazards. In press.

IMAGE team (2001) The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate change and impacts in the 21st century. Dutch Institute of Public Health and the Environment (RIVM), Bilthoven, The Netherlands.

IPCC (2001a) Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

IPCC (2001b) Climate Change 2001: Mitigation. Contribution of Working Group III to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

IPCC (2001c) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

Ittersum MK van, Leffelaar PA, Keulen H van, Kropff MJ, Bastiaans L, Goudriaan J (2003) On approaches and applications of the Wageningen crop models. European Journal of Agronomy 18: 201-234.

Kankaanpää S, Carter TR (2004) Construction of European forest land use scenarios for the 21st century. The Finnish Environment 707. Finnish Environment Institute, Helsinki, Finland.

Kasperson JX, Kasperson RE (2001) SEI Risk and Vulnerability, Programme Report 2001-01. Stockholm Environment Institute, Stockholm, Sweden.

Kates RW, Clark WC, Corell R, Hall JM, Jaeger CC, Lowe I, McCarthy JJ, Schellnhuber H-J, Bolin B, Dickson NM, Faucheux S, Gallopin GC, Grübler A, Huntley B, Jäger J, Jodha NS, Kasperson RE, Mabogunje A, Matson PA, Mooney HA, Moore III B, O'Riordan T, Svedin U (2001) Sustainability science. Science 292: 641-642.

Lambin EF, Rounsevell MDA, Geist H (2000) Are agricultural land use models able to predict changes in land use intensity? Agriculture Ecosystems and Environment 82: 321-331.

Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes O, Dirzo R, Fischer G, Folke C, George PS, Homewood K, Imbernon J, Leemans R, Li X, Moran EF, Mortimore M, Ramakrishnan PS, Richards JF, Skånes H, Steffen WL, Stone GD, Svedin U, Veldkamp TA, Vogel C, Xu J (2001) The causes of land use and land-cover change: moving beyond the myths. Global Environmental Change - Human and Policy Dimensions 11: 261-269.

Luers AL, Lobell DB, Sklar LS, Addams CL, Matson PA (2003) A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. Global Environmental Change 13: 255-267.

Meijden R van der, Duuren L van, Duistermaat LH (1996) Standard list of the flora of the Netherlands 1996. Survey of changes since 1990. Gorteria 22: 1-5.

Metzger M, Bunce B, Jongman R, Mateus V, Mücher S (2003) The Environmental Classification of Europe, a new tool for European landscape ecologists. Landschap 20: 50-54.

Metzger MJ, Leemans R, Schröter D, Cramer W, the ATEAM consortium (2004) The ATEAM vulnerability mapping tool. Quantitative Approaches in Systems Analysis No. 27, CD-ROM publication, Office C.T. de Wit Graduate School for Production Ecology & Resource Conservation (PE&RC), Wageningen, The Netherlands. [Available on the CD-ROM annex to this thesis]

Metzger MJ, Bunce RGH, Jongman RHG, Mücher CA, Watkins JW (2005a) A climatic stratification of the European environment. Global Ecology and Biogeography. In press. [Chapter 5 of this thesis]

Metzger MJ, Leemans R, Schröter D (2005b). A multidisciplinary, multi-scale framework for assessing vulnerabilities to global change. International Journal of Applied Geo-information and Earth Observation. In press. [Chapter 4 of this thesis]

Millennium Ecosystem Assessment (2003) Ecosystems and Human Well-being: a framework for assessment. Island Press, Washington DC, USA.

Mitchell TD, Carter TR, Jones PD, Hulme M, New M (2004) A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100). Tyndall Centre Working Paper No. 55. Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK.

Nakicenovic N, Alcamo J, Davis G, Vries B de, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, la Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, Rooyen S van, Victor N, Dadi Z (2000) IPCC Special Report on Emission Scenarios (SRES). Cambridge University Press, Cambridge, UK.

Reid WV, Mooney HA, Cropper A, Capistrano D, Carpenter SR, Chopra K, Dasgupta P, Dietz T, Duraiappah AK, Hassan R, Kasperson R, Leemans R, May RM, McMichael AJ, Pingali P, Samper C, Scholes R, Watson RT, Zakri AH, Shidong Z, Ash NJ, Bennett E, Kumar P, Lee MJ, Raudsepp-Hearne C, Simons H, Thonell J, Zurek MB (2005) Millennium Ecosystem Assessment Synthesis report. Island Press, Washington DC, USA.

Rounsevell MDA, Ewert F, Reginster I, Leemans R, Carter TR (2005a) Future scenarios of European agricultural land use II. Projecting changes in cropland and grassland. Agriculture Ecosystems and Environment 107: 117-135.

Rounsevell MDA, Reginster I, Araújo MB, Carter TR, Dendoncker N, Ewert F, House JI, Kankaanpää S, Leemans R, Metzger MJ, Schmit C, Smith P, Tuck G (2005b) A coherent set of future land use change scenarios for Europe. Agriculture Ecosystems and Environment. In press.

Schröter D, Acosta-Michlik L, Reidsma P, Metzger MJ, Klein RJT (2003) Modelling the Vulnerability of Eco-Social Systems to Global Change: Human Adaptive Capacity to Changes in Ecosystem Service Provision. Paper presented at the 5th Open Meeting of the Human Dimensions of Global Environmental Change Research Community, Montreal, Canada. [http://sedac.ciesin.columbia.edu/openmtg/]

Schröter D, Acosta-Michlik L, Arnell AW, Araújo MB, Badeck F, Bakker M, Bondeau A, Bugmann H, Carter T, Vega-Leinert AC de la, Erhard M, Espiñeira GZ, Ewert F, Friedlingstein P, Fritsch U, Glendining M, Gracia CA, Hickler T, House J, Hulme M, Klein RJT, Krukenberg B, Lavorel S, Leemans R, Lindner M, Liski J, Metzger MJ, Meyer J, Mitchell T, Mohren F, Morales P, Moreno JM, Reginster I, Reidsma P, Rounsevell MDA, Pluimers J, Prentice IC, Pussinen A, Sánchez A, Sabaté S, Sitch S, Smith B, Smith J, Smith P, Sykes MY, Thonicke K, Thuiller W, Tuck G, Werf G van der, Vayreda J, Wattenbach M, Wilson DW, Woodward FI, Zaehle S, Zierl B, Zudin S, Cramer W (2004) The ATEAM final report 2004 – Detailed report related to overall project duration. Advanced Terrestrial Ecosystem Analysis and Modelling, a project funded under the 5th Framework Programme of the European Union. [www.pik-potsdam.de/ateam/]

Schröter D, Polsky C, Patt AG (2005a) Assessing vulnerabilities to the effects of global change: an eight step approach. Mitigation and Adaptation Strategies for Global Change. In press.

Schröter D, Cramer W, Leemans R, Prentice IC, Araújo MB, Arnell NW, Bondeau A, Bugmann H, Carter TR, Garcia CA, Vega-Leinert AC de la, Erhard M, Ewert F, Glendining M, House JI, Kankaanpää S, Klein RJT, Lavorel S, Lindner M, Metzger MJ, Meyer J, Mitchell TD, Reginster I, Rounsevell M, Sabaté S, Sitch S, Smith B, Smith J, Smith P, Sykes MT, Thonicke K, Thuiller W, Tuck G, Zaehle S, Zierl B (2005b) Ecosystem Service Supply and Human Vulnerability to Global Change in Europe. Science. *Pending revisions.*

Smith JB, Schellnhuber H-J, Qader Mirza M, Fankhauser S, Leemans R, Erda L, Ogallo LA, Pittock BA, Richels R, Rosenzweig C, Safriel U, Tol RSJ, Weyant J, Yohe G (2001) Vulnerability to Climate Change and reasons for concern: A Synthesis. In: McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (eds) Climate Change 2001. Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, UK, pp 913-967.

Steffen W, Tyson P, Jäger J, Matson P, Moore B, Oldfield F, Richardson K, Schelnhuber J, Turner BL, Wasson R (2001) Global change and the earth system: a planet under pressure. IGBP Science 4: 2-32.

Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, Erasmus BFN, de Siqueira MF, Grainger A, Hannah L, Hughes L, Huntley B, Jaarsveld AS van, Midgley GF, Miles L, Ortega-Huerta MA, Peterson AT, Phillips OL, Williams SE (2004) Extinction risk from climate change. Nature 427: 145-148.

Thuiller W, Araújo MB, Lavorel S (2004) Do we need land-cover data to model species distributions in Europe? Journal of Biogeography 31: 353-361.

Turner BL II, Skole DL, Sanderson S, Fischer G, Fresco LO, Leemans R (1997) Land Use and Land-cover Change. Earth Science Frontiers 4: 26-33.

Turner BL II, Kasperson RE, Matson P, McCarthy JJ, Corell RW, Christensen L, Eckley N, Kasperson JX, Luers A, Martello ML, Polsky C, Pulsipher A, Schiller A (2003) A Framework for Vulnerability Analysis In Sustainability Science. Proceedings National Academy of Sciences USA 100: 8074-8079.

UNEP (2002) GEO-3: Global Environmental Outlook Report 3. UNEP - United Nations Environment Programme.

Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ (eds) (2000) Land Use, Land use Change and Forestry. A Special Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

World Conservation Monitoring Centre (1992) Global Biodiversity: Status of the Earth's living resources. Chapman & Hall, London, UK.

Yohe G, Tol RSJ (2002) Indicators for social and economic coping capacity -- moving toward a working definition of adaptive capacity. Global Environmental Change 12: 25-40.

Chapter 4

A multi-scale framework for assessing vulnerabilities to global change

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Abstract

Terrestrial ecosystems provide a number of vital services for people and society, such as food, fibre, water resources, carbon sequestration, and recreation. The future capability of ecosystems to provide these services is determined by changes in socio-economic factors, land use, atmospheric composition, and climate. Most impact assessments do not quantify the vulnerability of ecosystems and ecosystem services under such environmental change. They cannot answer important policy-relevant questions such as 'Which are the main regions or sectors that are most vulnerable to global change?' ; 'How do the vulnerabilities of two regions compare?' ; and 'Which scenario is the least harmful for a sector?'.

This chapter describes a new approach to vulnerability assessment developed by the ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling) project. Different ecosystem models, covering biodiversity, agriculture, forestry, hydrology, and carbon sequestration are fed with the same IPCC (Intergovernmental Panel on Climate Change) scenarios based on the *Special Report on Emissions Scenarios* (SRES). Each model gives insights into specific ecosystems, as in traditional impact assessments. Moreover, by integrating the results in a vulnerability assessment, the policy-relevant questions listed above can also be addressed. A statistically derived European environmental stratification forms a key element in the vulnerability assessment. By linking it to other quantitative environmental stratifications, comparisons can be made using data from different assessments and spatial scales.

Introduction

Many aspects of our planet are changing rapidly due to human activities and these changes are expected to accelerate during the next decades (IPCC, 2001abc). For example, forest area in the tropics is declining, many species are threatened to extinction, and atmospheric carbon dioxide concentration will soon be twice the concentrations in pre-industrial times, resulting in global warming. Many of these changes will have an immediate and strong effect on agriculture, forestry, biodiversity, human health and well-being, and on amenities such as traditional landscapes (UNEP, 2002 ; Watson *et al.*, 2000). Furthermore, a growing population, with increasing *per capita* consumption of food and energy, are expected to continue emitting pollutants to the atmosphere, resulting in continued nitrogen deposition and eutrophication of environments (Galloway, 2001 ; Alcamo, 2002). Both scientists and the general public have become increasingly aware that these environmental changes are part of a larger 'global change' (Steffen *et al.*, 2001). Many research projects and several environmental assessments are currently addressing these concerns at different scales, frequently in multidisciplinary collaborations. However, integrating this wealth of information across scales and disciplines remains a challenge (Millennium Ecosystem Assessment, 2003).

This chapter aims to quantify these global-change concerns in a regionally-explicit way by defining and estimating vulnerabilities. First, we summarize a comprehensive concept initially developed to assess which European people or sectors may be vulnerable to the loss of particular ecosystem services. These losses can be caused by the combined effects of changes in climate, land use, and atmospheric composition. The approach allows vulnerabilities to be compared across sectors, regions, and alternate futures. Subsequently, we illustrate how this concept can be applied at specific scales as well as across scales. The concepts described in this chapter were developed as part of the ATEAM project (Advanced Terrestrial Ecosystem Analysis and Modelling). Detailed information about the project can be found on its website (http://www.pik-potsdam.de/ateam).

Ecosystem services form a vital link between ecosystems and society by providing commodities such as food, timber, medicines, and fuels, by offering aesthetic and religious values, and by supporting essential ecosystem processes such as water purification (Daily, 1997). Impacts of global changes on ecosystems have already been observed (see reviews by Parmesan & Yohe, 2003 ; Root *et al.*, 2003) and influence human society. In addition to immediate global change effects on humans (e.g. sea-level rise or droughts), an important part of human vulnerability to global change is therefore caused by impacts on ecosystems and the services they provide (Millennium Ecosystem Assessment, 2003). In our vulnerability concept, the sustainable supply of ecosystem services is used as a measure of human well-being under the influence of global change threats. This is similar to the approach suggested by Luers *et al.*, (2003), who measured the vulnerability of Mexican farmers to decreasing wheat yields due to climate damage and market fluctuations.

The *Synthesis* chapter (Smith *et al.*, 2001) of the *Intergovernmental Panel on Climate Change* (IPCC) *Third Assessment Report* (TAR) recognized the limitations of traditional impact assessments, where limited climate-change scenarios were used to assess the response of a system at a future time. Smith *et al.* (2001) challenged the scientific community to move to more transient assessments that are a function of shifting environmental parameters (including climate) and socio-economic trends, and explicitly include the ability to innovate and adapt to the resulting changes. A step towards meeting this challenge is their definition of 'vulnerability':

Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes (IPCC, 2001a).

Although this definition addresses climate change only, it also includes susceptibility, which is a function of exposure, sensitivity, and adaptive capacity. The vulnerability concept developed for ATEAM is a further elaboration of this definition and is especially developed to integrate results from a broad range of models and scenarios. Projections of changing supply of different ecosystem services and scenario-based changes in adaptive capacity are integrated into vulnerability maps for different socio-economic sectors (i.e. agriculture, forestry, water management, energy, and nature conservation). These vulnerability maps provide a means for making comparisons between ecosystem services, sectors, scenarios and regions to tackle questions such as:

- Which regions are most vulnerable to global change ?
- How do the vulnerabilities of two regions compare ?
- Which sectors are the most vulnerable in a certain region ?
- Which scenario is the least harmful for a sector ?

The term vulnerability was thus defined in such a way that it includes both the traditional elements of an impact assessment (i.e. potential impacts of a system to exposures), and adaptive capacity to cope with potential impacts of global change (Schröter *et al.*, 2004 ; Turner *et al.*, 2003).

The following sections first summarise the concepts of the spatially explicit and quantitative framework that was developed for a vulnerability assessment for Europe, explaining the different tools used to quantify the elements of vulnerability, and how we integrate these elements into maps of vulnerability. Then we illustrate how the vulnerability framework can be used to compare information from the global impact model IMAGE (IMAGE team, 2001) with the European results from ATEAM.

The multidisciplinary vulnerability framework

The IPCC definitions of vulnerability to climate change, and related terms such as exposure, sensitivity, and adaptive capacity, form a suitable starting position to explore possibilities for quantification. However, because vulnerability assessments consider not only climate change, but also other global changes such as land-use change (Turner *et al.*, 2003), the IPCC definitions were broadened. Table 3.1 lists the definitions of some fundamental terms used in this chapter and gives an example of how these terms could relate to the agriculture sector. From these definitions the following generic functions are constructed, describing the vulnerability of a sector relying on a particular ecosystem service in an area under a certain scenario at a certain point in time. Vulnerability is a function of exposure, sensitivity and adaptive capacity (equation 1). Potential impacts are a function of exposure and sensitivity (equation 2). Therefore, vulnerability is a function of potential impacts and adaptive capacity (equation 3):

$$V(es, x, s, t) = f\left(E(es, x, s, t), S(es, x, s, t), AC(es, x, s, t) \right) \quad (1)$$

$$PI(es, x, s, t) = f\left(E(es, x, s, t), S(es, x, s, t) \right) \quad (2)$$

$$V(es, x, s, t) = f\left(PI(es, x, s, t), AC(es, x, s, t) \right) \quad (3)$$

where V = vulnerability, E = exposure, S = sensitivity, AC = adaptive capacity and PI = potential impact, es = ecosystem service, x = a grid cell, s = a scenario, t = a time slice.

These simple conceptual functions describe how the different elements of vulnerability are related to each other. Nevertheless, they are not immediately operational for converting model outputs into vulnerability maps. The following sections describe how modelled maps of any ecosystem service can be converted into vulnerability maps that will allow for multidisciplinary intercomparison, such as between ecosystem services relevant for forestry and agriculture.

The vulnerability methodology will be illustrated by using the agricultural ecosystem service *farmer livelihood*. In the European Union, farmer livelihood is primarily determined by subsidies, not yield. Therefore the percentage cultivated agricultural land, as determined by the ATEAM land use scenarios (Rounsevell *et al.*, 2005a ; Ewert *et al.*, 2005) is used as an indicator. Agricultural land is defined as the sum of arable land, grassland used for grazing, and land used for biomass energy crop production ('biofuels'). Changes in agricultural land use were calculated from demand-supply relationships considering effects on productivity of climate change, increasing CO_2 concentration and technological development. Allocation of land use was based on scenario-specific assumptions about policy regulations, urban development, nature conservation and land availability. The following sections elaborate on, and quantify, the elements of the vulnerability functions for *farmer livelihood*, resulting in vulnerability maps for people interested in the agriculture sector.

Exposure, sensitivity and potential impacts

Exposure is represented by IPCC scenarios of the main global change drivers, based on the *Special Report on Emissions Scenarios* (SRES) (Nakicenovic *et al.*, 2000). SRES consists of a comprehensive set of narratives that define the local, regional and global socio-economic driving forces of environmental change (e.g. demography, economy, technology, energy, and agriculture). The SRES scenarios are structured in four major 'families' labelled A1, A2, B1 and B2, each of which emphasizes a largely different set of social and economic ideals. These ideals are organized along two axes. The vertical axis represents a distinction between more economically (A) and more environmentally and equity (B) orientated futures. The horizontal axis represents the range between more globalization (1) and more regionally-oriented developments (2). Fig. 4.1 gives a summary of the main trends in the ATEAM land use scenarios (Rounsevell *et al.*, 2005ab).

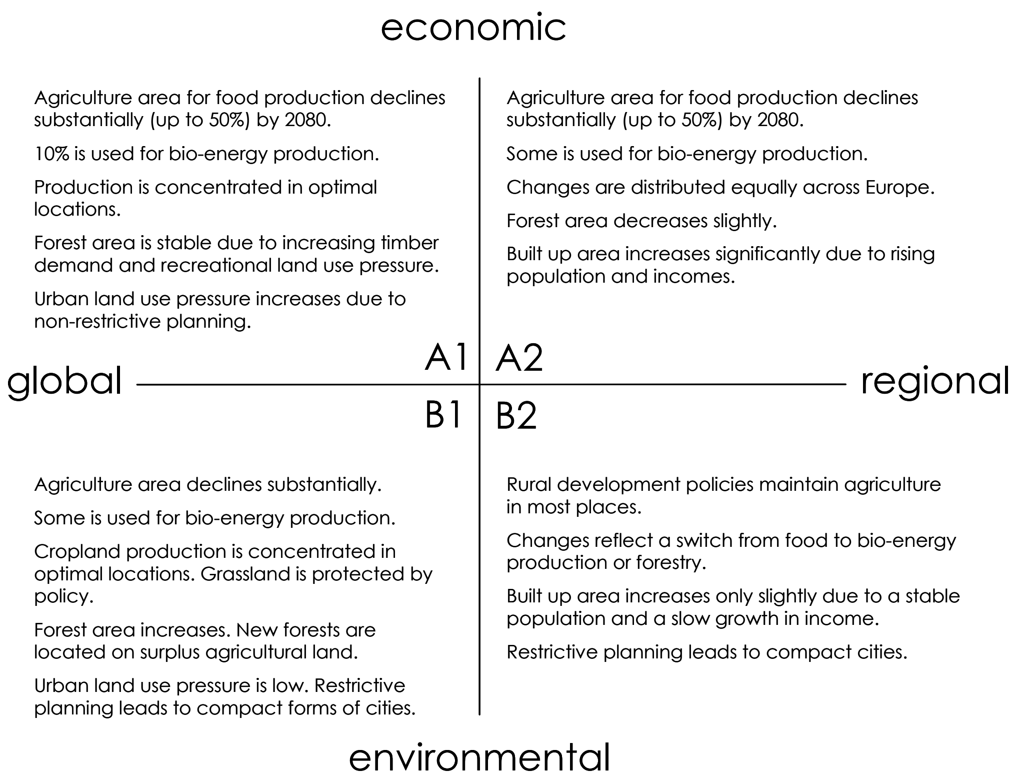

Figure 4.1. Summary of the main trends in the ATEAM land use scenarios (Rounsevell *et al.*, 2005a), following the IPCC SRES storylines (Nakicenovic *et al.*, 2000).

Besides for land use, discussed in the previous section, scenarios were also developed for atmospheric carbon dioxide concentration, climate, socio-economic variables. These scenarios are internally consistent, and considered explicitly the global context (import and export) of European land use. The IMAGE implementation (IMAGE team, 2001) of these scenarios was used to define the global context (trade, socio-economic trends, demography, global emissions and atmospheric concentrations, climate change levels). The narratives provided the basis to further interpret and quantify the European factors to develop the high-resolution (10 arcmin x 10 arcmin, approximately 16 km x 16 km in Europe) scenarios required by this vulnerability assessment for the period 2000 to 2100. By using the SRES scenarios, the vulnerability assessment spans a wide range of plausible futures. Additionally, these four different European SRES scenarios were linked to four different climate-change patterns obtained from Global Climate Models (GCMs). These multiple GCMs are used to indicate the variability in estimates of future European climates (see also Ruosteenoja *et al.*, 2003).

The vulnerability maps are created for three time slices (1990-2020, 2020-2050, 2050-2080). Ecosystem service provision is estimated by ecosystem models as a function of ecosystem sensitivity and global change exposure. The resulting range of outputs for each ecosystem service indicator enables the differentiation of regions that are impacted under most scenarios, regions that are impacted under specific scenarios, and regions that are not impacted under any scenario.

In the examples mapped in this chapter we restrict ourselves to the ecosystem service *farmer livelihood* (Fig. 4.1). For this ecosystem service, the vulnerability approach is illustrated with maps for one GCM, the Hadley Centre Climate Model 3 (HadCM3), and one scenario, the A1 scenario, which assumes continued globalization with a focus on economic growth. The analysis of multiple scenarios is discussed in a separate section.

Stratified potential impacts

Our estimation of potential impacts is undertaken at the regional scale, emphasizing the differences across the European environment. Simply comparing changes in ecosystem services across Europe provides only a limited analysis of regional differences because ecosystem services are highly correlated with their environments. Some environments have high values for particular ecosystem services, whereas other regions have lower values. For instance, Spain has high biodiversity (5048 vascular plant species (WCMC, 1992)), but low grain yields (2.7 t ha^{-1} for 1998-2000 average (Ekboir, 2002)), whereas The Netherlands has a far lower biodiversity (1477 vascular plant species (Meijden van der *et al.*, 1996)), but a high grain yield (8.1 t ha^{-1} for 1998-2000 average (Ekboir, 2002)). Therefore, while providing useful information about the stock of resources at a European scale, absolute differences in species numbers or yield levels are not good measures for comparing regional impacts between these countries. Looking at relative change in ecosystem service provision would overcome this problem (e.g. –40% grain yield in Spain *versus* +8% in The Netherlands), but also has a serious limitation: the same relative change can occur in very different situations. Tables 3.2 and 3.3 illustrate how a relative change of –20% can represent very different impacts, both between and within environments. Therefore comparisons of relative changes in single grid cells must be interpreted with great care and cannot easily be compared.

For a meaningful comparison of grid cells across Europe it is necessary to place potential impacts in their regional environmental context, i.e. in a justified cluster of environmental conditions that is suited as a reference for the values in an individual grid cell. Because environments will alter under global change, consistent environmental strata must be determined for each time slice. We used the recently developed *Environmental Stratification of Europe* (EnS) to stratify the modelled potential impacts (Chapters 5 and 6 ; Metzger *et al.*, 2005). The EnS was created by statistical clustering of selected climate and topographical variables into 84 strata. For each stratum a discriminant function was calculated for the variables available from the climate change scenarios. With these functions the 84 climate classes were mapped for the different GCMs, scenarios and time slices, resulting in 48 maps of shifted climate classes. Maps of the EnS, for baseline and the HadCM3-A1 scenario are mapped in Fig. CP1.2 for aggregated Environmental Zones. With these maps, all modelled potential impacts on ecosystems can be placed in their environmental context consistently.

Within an environmental stratum ecosystem service values can be expressed relative to a reference value. While any reference value is inevitably arbitrary, in order to make comparisons it is important that the stratification is performed consistently. The reference value used in this assessment is the highest ecosystem service value achieved in an environmental stratum. This measure can be compared to the concept of potential yield, defined by growth-limiting environmental factors (Ittersum van *et al.*, 2003). For a grid cell in a given EnS stratum, the fraction of the modelled ecosystem service provision relative to the highest achieved ecosystem service value in the region (ESref) is calculated, giving a stratified value of the ecosystem service provision (ESstr) with a 0-1 range for the ecosystem service in the grid cell:

$$ESstr_{(es, x, s, t)} = ES_{(es, x, s, t)} / ESref_{(es, ens, x, s, t)} \quad (4)$$

where ESstr = stratified ecosystem service provision, ES = ecosystem service provision and ESref = highest achieved ecosystem service value, es = ecosystem service, x = a grid cell, s = a scenario, t = a time slice and EnS = an environmental stratum

In this way a map is created in which potential impacts on ecosystem services are stratified by their environment and expressed relative to a reference value (Fig. CP4.2). Because the environment changes over time, both the reference value and the environmental stratification are determined for each time slice. As shown in Fig. CP4.2, the stratified ecosystem service provision map shows more regional detail than the original non-stratified map. This is the regional detail required to compare potential impacts across regions (see also Tables 3.2 and 3.3). The change in stratified ecosystem service provision compared to baseline conditions shows how potential changes in ecosystem services affect a given location (see also Tables 3.2 and 3.3). Regions where ecosystem service supply relative to the environment increases have a positive change in potential impact and *vice versa* (see Fig. CP5.1). This is for instance the case when environmental conditions become less favourable for growing wheat, but yield levels are maintained. This change in ESstr (equation 5) gives a measure of stratified potential impact (PIstr), which is used to estimate vulnerability (see below).

$$PIstr_{(es, x, s, t)} = ESstr_{(es, x, s, t)} - ESstr_{(es, x, s, baseline)} \quad (5)$$

where PIstr = stratified potential impact, ESstr = stratified ecosystem service supply, es = ecosystem service, x = a grid cell, s = a scenario, t = a time slice, baseline = 1990.

Adaptive capacity index

Adaptation in general is understood as an adjustment in natural or human systems in response to actual or expected environmental change, which moderates harm or exploits beneficial opportunities. Here, adaptive capacity reflects the potential to implement planned adaptation measures and is therefore concerned with deliberate human attempts to adapt to or cope with change, and not with autonomous adaptation.

The concept of adaptive capacity was introduced in the *IPCC Third Assessment Report* (IPCC, 2001a). According to the IPCC, factors that determine adaptive capacity to climate change include economic wealth, technology and infrastructure, information, knowledge and skills, institutions, equity and social capital. So far, only one study has made an attempt at quantifying adaptive capacity based on observations of past hazard events (Yohe & Tol, 2002). For the vulnerability assessment framework, present-day and future estimates of adaptive capacity were sought that would be quantitative, spatially explicit, and based on, as well as consistent with, the different exposure scenarios described above. In ATEAM we developed a generic index of macro-scale adaptive capacity. This index is based on a conceptual framework of socio-economic indicators, determinants and components of adaptive capacity, e.g. GDP per capita, female activity rate, income inequality, number of patents, and age dependency ratio (Schröter *et al.*, 2003 ; Klein *et al.*, in preparation to be submitted to *Global Environmental Change Part A: Human and Policy Dimensions*). The index is calculated for smaller regions (i.e. provinces and counties) and differs for each SRES scenario. The index does not include individual abilities to adapt. An illustrative example of our spatially explicit generic adaptive capacity index over time is shown in Fig. CP3.1, for the A1 scenario. Different regions in Europe show different adaptive capacities – under this A1 scenario, lowest adaptive capacity is expected in the Mediterranean, but the differences decline over time.

Vulnerability maps

The different elements of the vulnerability function (equation 3) have now been quantified (cf Fig. CP6). The last step, the combination of stratified potential impact (PIstr) and the adaptive capacity index (AC), is however the most dangerous step, especially when taking into account the limited empirical basis of the adaptive capacity index. It was therefore decided to create a visual combination of PIstr and AC without quantifying a specific relationship. The vulnerability maps (Fig. CP5.2) illustrate which areas are vulnerable. For further analytical purposes the constituents of vulnerability, the changes in potential impact and the adaptive capacity index, will have to be viewed separately.

Trends in vulnerability follow the trend in potential impact: when ecosystem service supply decreases, humans relying on that particular ecosystem service become more vulnerable in that region. Alternatively, vulnerability decreases when ecosystem service supply increases. Adaptive capacity lowers vulnerability. In regions with similar changes in potential impact, the region with a high AC will be less vulnerable than the region with a low AC. The Hue Saturation Value (HSV) colour scheme is used to combine PIstr (Fig. CP5.1) and AC (Fig. CP3.1). The PIstr determines the Hue, ranging from red (decreasing ecosystem service provision, PIstr = –1, highest negative potential impact) via yellow (no change in ecosystem service provision, PIstr = 0, no potential impact) to green (increase in ecosystem service supply, PIstr = 1, highest positive potential impact). Note that it is possible that while the modelled ecosystem service supply (Fig. 4.1) stays unchanged, stratified potential impact increases or decreased due to changes in the highest value of ecosystem service supply in the environmental stratum (ESref). Thus, when the environment changes this is reflected in a change in potential impact.

Colour saturation is determined by the AC and ranges from 50% to 100% depending on the level of the AC. When the PIstr becomes more negative, a higher AC will lower the vulnerability, therefore a higher AC value gets a lower saturation, resulting in a less bright shade of red. Alternatively, when ecosystem service supply increases (PIstr > 0), a higher AC value will get a higher saturation, resulting in a brighter shade of green. Inversely, in areas of negative impact, low AC gives brighter red, whereas in areas of positive impacts low AC gives less bright green.

The last element of the HSV colour code, the Value, was kept constant for all combinations. Fig. CP5.2 shows the vulnerability maps and the legend for farmer livelihood under the A1 scenario (see also Fig. 4.1) for the HadCM3 GCM. Under this scenario *farmer livelihood* will decrease in the extensive agricultural areas. The role of AC becomes apparent in rural France and Spain, where France is less vulnerable than Spain due to a higher AC, i.e. a supposed higher ability of the French agricultural sector to react to these changes.

Analysis of the maps

Spatially modelling ecosystem services and potential impacts and vulnerability clearly shows that global changes will impact ecosystems and humans differently across Europe. Therefore these maps provide insights that cannot be obtained through non-spatial modelling. However, interpreting the spatial patterns portrayed in the multitude of maps (related to multiple ecosystem services, scenarios, and time slices) is difficult. To make the results more accessible, both to stakeholders and scientists, many of the analyses can take place in summarized form. For instance, changes can be summarized per (current) Environmental Zone (EnZ) (Fig. CP1.2, 1990) or per country. In such graphs, multiple scenarios can be analysed for different regions. Similar graphs can be made to examine the development over time for a specific region. All maps generated by the ATEAM projects are available in a software tool can allows both simple map queries and the construction of summarising scatter plots (Metzger *et al.*, 2004 ; available on the CD-ROM annex to this thesis).

Fig. 3.12 gives an example of a summary of the changes in PIstr for the 2080 time slice (compared to baseline). Similar graphs can be made for the other components of vulnerability and to illustrate variability between modelled results obtained using climate change scenarios generated by different

GCMs, as demonstrated in Metzger *et al.* (2004). The results presented in Fig. 3.12 show that the SRES scenarios affect PIstr differently in the different regions. In most cases the A1 scenario has the most negative impact. However, in the Atlantic Central the A2 and B2 scenarios project greater changes. The B1 scenario most frequently shows the smallest impact, but not in the Mediterranean South, where it comes third, after A2 and B2.

Multi-scale comparisons of vulnerability

Ecosystems are frequently hierarchically grouped, for instance in local vegetation units (i.e. stands), landscapes and biomes. Traditional assessments usually focus on the impacts of a limited number of drivers on a subset of ecosystems within one of these groups (e.g. Luers *et al.*, 2003 ; Polsky, 2004). Unfortunately integrating and comparing observations drawn from different studies remains a great challenge (Millennium Ecosystem Assessment, 2003). This section illustrates how the presented vulnerability framework presented above can be applied at the other scales, using suitable stratifications for that scale. Furthermore, by linking stratifications, results from the global impact model IMAGE (IMAGE team, 2001) will be compared with the European results from ATEAM.

Vulnerability maps at different scales

It is generally recognized that ecosystem components determine spatial environmental patterns through a scale-dependant hierarchy. On a global or continental scale, climate and geology determine the main patterns. They are conditional for the formations of soils, which in turn determine the local potential vegetation. There are feedbacks in the other direction, for example vegetation also influences soil properties and can even influence local climate. Most ecosystem patterns are, however, caused by the above-mentioned hierarchy (Bailey, 1985 ; Klijn & de Haes, 1994). On a European scale, climate and geomorphology are recognized as the key determinants of ecological patterns ; these are followed by geology and soil. The variables that were clustered to create the European Environmental Stratification, which was used to stratify ecosystem service supply in Europe as described above, were selected with this conceptual hierarchical model in mind (Chapter 5 ; Metzger *et al.*, 2005).

In studies where ecosystem service supply is modelled at other scales, e.g. globally or at the catchment level, similar quantitative stratifications can be created using variables that are appropriate for that particular scale. With these stratifications it will then be possible to stratify potential impacts. At the global scale, several modelled maps of potential natural vegetation or biomes are available that could form suitable quantitative stratifications and are also linked to global change scenarios. Fig. CP7 shows how global stratified potential impact maps can be created in the same way as depicted in Fig. CP5.1 for Europe, using data from the dynamic integrated assessment modelling framework IMAGE 2.2 (IMAGE team, 2001). IMAGE was developed over the last 15 years and has been used extensively to explore potential impacts of global change at the global level. Potential natural vegetation (biomes), as modelled by IMAGE, is used to stratify the ecosystem service food crop production. Because no adaptive capacity index is available at the global scale it is not possible at this time to create vulnerability maps, as shown in Fig. CP5.2.

Quantitative stratifications at the more regional levels (i.e. catchment or landscape) are currently not readily available, but could be created with a specific region in mind. Furthermore, advances in quantitative clustering and classification make consistent regional landscape maps possible over large areas, as demonstrated by the first stages of the European landscape character assessment by Mücher *et al.* (2003).

Comparing across scales

As demonstrated above, vulnerability maps at different scales can be created, as long as both a suitable quantitative stratification and adaptive capacity data are available. However, while stratified potential impact and vulnerability maps of different scenarios or sectors can be compared at one scale, the European maps of Fig. CP5.1 cannot be compared to the global maps of Fig. CP7 because these maps are based on different stratifications. This can be overcome by either applying the IMAGE biome stratification on the ATEAM data or *vice versa*.

It is difficult to apply the 84 class EnS on the IMAGE data, since at the 0.5° resolution (approximately 50 km x 50 km in Europe) more than 10% of the EnS classes cover fewer than 10 grid cells. The other option, applying the IMAGE biome stratification on the ATEAM data, would result in a great loss of information, because the ATEAM data (10 arcmin x 10 arcmin ; approximately 16 km x 16 km in Europe) would have to be resampled to the resolution of the IMAGE data. However, comparisons at the ATEAM resolution will be possible if the two stratification schemes, the *Environmental Stratification of Europe* (EnS) and the IMAGE biomes, can be linked.

The strength of agreement between an aggregation of the EnS and the IMAGE biomes was determined by calculating the Kappa statistic (Monserud & Leemans, 1992). For the Kappa analysis the datasets that are compared must have the same spatial resolution, and distinguish the same classes. To meet these requirements the EnS was resampled to the IMAGE resolution and the two classifications were clipped to the largest overlapping extent. A contingency matrix was calculated to determine the best way to aggregate the EnS strata. Kappa, 0.719, could then be calculated using the Map Comparison Kit (Visser, 2004), which indicates a 'very good' strength of agreement between the aggregated EnS and the IMAGE biomes (Monserud & Leemans, 1992). Fig. CP8 shows the Kappa statistic for the whole map as well as for the different biomes.

The strong agreement between the aggregated EnS and the IMAGE biomes indicates that it is possible to stratify the fine resolution ATEAM model outputs by the IMAGE biomes, thus placing the European maps in the global context. The resulting European maps of stratified potential impact of ***farmer livelihood*** at 10 arcmin x 10 arcmin resolution can now be compared to the global maps of ***total crop production*** derived from IMAGE, as shown in Fig. CP9.

A comparison between the two ecosystem services shows regions with similar potential impact (e.g. the grass lands and scrubland in the Mediterranean and the boreal forest in Scandinavia). In other regions, e.g. France, the maps show opposite trends. The analysis of the difference in the maps goes beyond the scope of this chapter; however these maps do illustrate how the analysis of maps of stratified potential impact can help answer policy-relevant questions such as those outlined in the introduction.

Discussion and conclusions

This chapter has demonstrated the ATEAM vulnerability approach with the example of two agricultural ecosystem services, modelled at different scales, which provides insight into the type of analyses that can be made with this framework. However, it cannot be seen as a comprehensive vulnerability assessment, which needs to include more sectors and scenarios. Only then will it be possible to consider interactions between different ecosystem services and between sectors. For example, abandoning agricultural areas not only influences the farming community, but also has implications for the aesthetic value of a landscape, and therefore for the tourism sector. Since the described vulnerability framework presents ecosystem services in a common dimension, we suggest that this framework can form a useful tool for users to examine possible interactions between sectors.

The current framework was developed with the tools at hand and a wish list of analyses in mind. Strong points in the framework are the multiple scenarios as a measure of variability and uncertainty, the multiple stressors (CO_2

concentrations, climate, and land use), the inclusion of a measure of adaptive capacity, and the possibility to make comparisons across different scales. The approach, as presented here, will facilitate the analysis of the ecosystem services estimated by ecosystem models. As the approach is applied, more advanced methods of combining stratified potential impact (PIstr) and adaptive capacity (AC) may be developed. However, prerequisite for this is a further understanding of how PIstr and AC interact and influence vulnerability, which may only be feasible when empirically analysing specific cases. Ideally, the AC index will eventually be replaced by sector specific projections of adaptive capacity. Some qualitative information, or knowledge shared during stakeholder dialogues does not enter the approach in a formal way. Therefore it is imperative to discuss the results with stakeholders, experts and scientists as part of the analysis.

Communication of the results of a vulnerability assessment will need considerable thought, not in the least because of the uncertainties in future changes, and the political sensitivity around (European) policies that are directly related, such as agricultural reforms and carbon trading. Vulnerability maps, as well as maps of the exposure, ecosystem service supply, PI, PIstr, and AC, should always be presented as one of a range of possible scenarios. Furthermore, many of the comparisons and analyses can take place in summarized tables or graphs, which can present multiple scenarios and time slices, instead of single maps, as shown in Fig. 3.12.

The method of comparing vulnerability, and its components, across scales by using a nested hierarchy of stratifications offers a challenging new way of analysis. However, as argued by O'Brien *et al.* (2004), vulnerability is a dynamic outcome of both environmental and social processes occurring at multiple scales. While the nested stratifications form a tool for analysing multi-scale environmental processes, they neglect the social aspects. Therefore, when vulnerability maps based on this framework depict problematic regions, further attention should be directed to these regions to analyse their adaptive capacity at different scales (e.g. household, municipality, province, country).

This work was guided by the vision that scientists can support stakeholders in decision-making and resource management processes. In order to enable citizens to best decide how to manage their land in a sustainable way, multiple maps of potential changes in ecosystem service supply and adaptive capacity of related sectors could be generated for all the ecosystem services that are relevant to the people. Like a portfolio that is spatially explicit and shows projections over time (while being honest about the attached uncertainties), different ecosystem services could be seen in their interactions, sometimes competing with each other, sometimes erasing or enforcing each other. This portfolio could provide the basis for discussion between different stakeholders and policymakers, thereby facilitating sustainable management of natural resources. This chapter has shown how such a portfolio can be made for different spatial scales, and how maps from different scales can be compared using nested quantitative stratifications.

References

Alcamo J (2002). Introduction to special issue on regional air pollution and climate change in Europe. Environmental Science & Policy 5: 255.

Bailey RG (1985) The factor of scale in ecosystem mapping. Environmental Management, 9: 271-276.

Daily GC (1997) Nature's services. Island Press / Shearwater Books, Washington DC, USA.

Ekboir J (ed) (2002) CIMMYT 2000-2001 World Wheat Overview and Outlook: Developing No-Till Packages for Small-Scale Farmers. CIMMYT, Mexico.

Ewert F, Rounsevell MDA, Reginster I, Metzger MJ, Leemans R (2005) Future scenarios of European agricultural land use. I: Estimating changes in crop productivity. Agriculture, Ecosystems and Environment 107: 101-116.

Galloway JN (2001) Acidification of the world: Natural and anthropogenic. Water, Air, and Soil Pollution 130: 17-24.

IMAGE team (2001) The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate change and impacts in the 21st century. Dutch Institute of Public Health and the Environment (RIVM), Bilthoven, The Netherlands.

IPCC (2001a) Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

IPCC (2001b) Climate Change 2001: Mitigation. Contribution of Working Group III to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

IPCC (2001c) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

Ittersum MK van, Leffelaar PA, Keulen H van, Kropff MJ, Bastiaans L, Goudriaan J (2003) On approaches and applications of the Wageningen crop models. European Journal of Agronomy 18: 201-234.

Klijn F, Haes HAU de (1994) A hierarchical approach to ecosystems and its implications for ecological land classification. Landscape Ecology 9: 89-104.

Luers AL, Lobell DB, Sklar LS, Addams CL, Matson PA (2003) A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. Global Environmental Change 13: 255-267.

Meijden R van der, Duuren L van, Duistermaat LH (1996) Standard list of the flora of the Netherlands 1996. Survey of Changes since 1990. Gorteria 22: 1-5.

Metzger MJ, Leemans R, Schröter D, Cramer W, and the ATEAM consortium (2004) The ATEAM vulnerability mapping tool. Quantitative Approaches in Systems Analysis No. 27, CD-ROM publication, Office C.T. de Wit Graduate School for Production Ecology & Resource

Conservation (PE&RC), Wageningen, The Netherlands. [Available on the CD-ROM annex to this thesis]

Metzger MJ, Bunce RGH, Jongman RHG, Mücher CA, Watkins J (2005). A climatic stratification of the environment of Europe. Global Ecology and Biogeography. In press. [Chapter 5 of this thesis]

Monserud RA, Leemans R (1992) The comparison of global vegetation maps. Ecological Modelling 62: 275-293.

Mücher CA, Bunce RGH, Jongman RHG, Klijn JA, Koomen AJM, Metzger MJ, Wascher DM (2003). Identification and Characterisation of Environments and Landscapes in Europe. Alterra report 832. Alterra, Wageningen UR, Wageningen, The Netherlands.

Millennium Ecosystem Assessment (2003). Ecosystems and Human Well-being: a framework for assessment. Island Press, Washington DC, USA.

Nakicenovic N, Alcamo J, Davis G, Vries B de, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, la Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, Rooyen S van, Victor N, Dadi Z (2000) IPCC Special Report on Emission Scenarios (SRES). Cambridge University Press, Cambridge, UK.

O'Brien K, Sygna L, Haugen JE (2004). Vulnerable or resilient? A multi-scale assessment of climate impacts and vulnerability in Norway. Climatic Change 64: 193-225.

Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421: 37-42.

Polsky C (2004). Putting Space and Time in Ricardian Climate Change Impact Studies: The Case of Agriculture in the U.S. Great Plains, Annals of the Association of American Geographers 94: 549-564.

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421: 57-60.

Rounsevell MDA, Ewert F, Reginster I, Leemans R, Carter TR (2005a) Future scenarios of European agricultural land use. II: projecting changes in cropland and grassland. Agriculture Ecosystems and Environment 107: 117-136.

Rounsevell MDA, Reginster I, Araújo MB, Carter TR, Dendoncker N, Ewert F, House JI, Kankaanpää S, Leemans R, Metzger MJ, Schmit C, Smith P, Tuck G (2005b) A coherent set of future land use change scenarios for Europe. Agriculture Ecosystems and Environment. In press.

Ruosteenoja K, Carter TR, Jylhä K, Tuomenvirta H (2003) Future climate in world regions: an intercomparison of model-based projections for the new IPCC emissions scenarios. The Finnish Environment 644. Finnish Environment Institute, Helsinki, FInland.

Schröter D, Acosta-Michlik L, Reidsma P, Metzger MJ, Klein RJT (2003) Modelling the Vulnerability of Eco-Social Systems to Global Change: Human Adaptive Capacity to Changes in Ecosystem Service Provision. Paper presented at the 5th Open Meeting of the Human Dimensions of Global Environmental Change Research Community, Montreal, Canada. [http://sedac.ciesin.columbia.edu/openmtg/]

Schröter D, Acosta-Michlik L, Arnell AW, Araújo MB, Badeck F, Bakker M, Bondeau A, Bugmann H, Carter T, Vega-Leinert AC de la, Erhard M, Espiñeira GZ, Ewert F, Friedlingstein P, Fritsch U, Glendining M, Gracia CA, Hickler T, House J, Hulme M, Klein RJT, Krukenberg B, Lavorel S, Leemans R, Lindner M, Liski J, Metzger MJ, Meyer J, Mitchell T, Mohren F, Morales P, Moreno JM, Reginster I, Reidsma P, Rounsevell MDA, Pluimers J, Prentice IC, Pussinen A, Sánchez A, Sabaté S, Sitch S, Smith B, Smith J, Smith P, Sykes MY, Thonicke K, Thuiller W, Tuck G, Werf G van der, Vayreda J, Wattenbach M, Wilson DW, Woodward FI, Zaehle S, Zierl B, Zudin S, Cramer W (2004) The ATEAM final report 2004 – Detailed report related to overall project duration. Advanced Terrestrial Ecosystem Analysis and Modelling, a project funded under the 5th framework Programme of the European Union. [www.pik-potsdam.de/ateam/]

Schröter D, Polsky C, Patt AG (2005). Assessing vulnerabilities to the effects of global change: an eight step approach. Mitigation and Adaptation Strategies for Global Change. In press.

Smith JB, Schellnhuber H-J, Qader Mirza M, Fankhauser S, Leemans R, Erda L, Ogallo LA, Pittock BA, Richels R, Rosenzweig C, Safriel U, Tol RSJ, Weyant J, Yohe G (2001) Vulnerability to Climate Change and reasons for concern: A Synthesis. In: McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (eds) Climate Change 2001. Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, UK, pp 913-967.

Steffen W, Tyson P, Jäger J, Matson P, Moore B, Oldfield F, Richardson K, Schelnhuber J, Turner BL, Wasson R (2001) Global change and the earth system: a planet under pressure. IGBP Science 4: 2-32.

Turner BL II, Kasperson RE, Matson P, McCarthy JJ, Corell RW, Christensen L, Eckley N, Kasperson JX, Luers A, Martello ML, Polsky C, Pulsipher A, Schiller A (2003) A Framework for Vulnerability Analysis In Sustainability Science. Proceedings National Academy of Sciences USA 100: 8074-8079.

UNEP (2002) GEO-3: Global Environmental Outlook Report 3. UNEP - United Nations Environment Programme.

Visser H (2004) The Map Comparison Kit: methods, software and applications. RIVM report 550002005/2004. Bilthoven, The Netherlands.

Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ (eds) (2000) Land Use, Land-Use Change and Forestry. A Special Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

World Conservation Monitoring Centre (1992) Global Biodiversity: Status of the Earth's living resources. Chapman & Hall, London, UK.

Yohe G, Tol RSJ (2002) Indicators for social and economic coping capacity -- moving toward a working definition of adaptive capacity. Global Environmental Change 12: 25-40.

Chapter 5

A climatic stratification of the environment of Europe

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Global Ecology and Biogeography, in press.

Abstract

Aim

To produce a statistical stratification of the European environment, suitable for stratified random sampling of ecological resources, the selection of sites for representative studies across the continent, and to provide strata for modelling exercises and reporting.

Location

A 'Greater European Window' with the following boundaries: 11°W, 32°E, 34°N, 72°N.

Methods

Twenty of the most relevant available environmental variables were selected, based on experience from previous studies. Principal Components Analysis (PCA) was used to explain 88% of the variation into three dimensions, which were subsequently clustered using an ISODATA clustering routine. The mean first principal component values of the classification variables were used to aggregate the strata into Environmental Zones and to provide a basis for consistent nomenclature.

Results

The *Environmental Stratification of Europe* (EnS) consists of 84 strata, which have been aggregated into 13 Environmental Zones. The stratification has a 1 km^2 resolution. Aggregations of the strata have been compared to other European classifications using the Kappa statistic, and show 'good' comparisons. The individual strata have been described using data from available environmental databases. The EnS is available on the CD-ROM annex in the back of this thesis.

Main conclusions

The *Environmental Stratification of Europe* has been constructed using tried-and-tested statistical procedures. It forms an appropriate stratification for stratified random sampling of ecological resources, the selection of sites for representative studies across the continent and for the provision of strata for modelling exercises and reporting at the European scale.

Introduction

In order to place field observations into the European context, it is necessary to find standardised methods of synthesizing environmental data into strata which will permit objective aggregation. The development of a statistical classification of environmental conditions is the first step in the production of a tool for deriving stratified random samples, because it allows areas and situations to be compared in a reproducible way (Bunce *et al.*, 1996a). On a continental scale of spatial research, e.g. biodiversity monitoring, data comparisons, and scenario building for the European Union (EU), a stratification of land into more or less homogeneous regions would provide a valuable framework since statistical inference requires sample data to be representative of a defined population (Cochran, 1977).

Within a stratum, or sub-population, changes or effects can, as far as possible, be analysed separately from environmental heterogeneity by using standard statistical procedures (Cochran, 1977 ; Bunce *et al.*, 1996a). For example, agricultural land abandonment can affect species abundance and it could be important to asses the impact of this process on biodiversity in Europe. However, because species abundance is also dependant on wider-scale, more stable, aspects of the environment, it is difficult to assess whether changes in species abundance are indeed caused by abandonment or by inherent differences in environments. Environmental stratification will provide a context within which analyses of dynamic change can be safely extrapolated. In the example, this makes it possible to determine whether differences in species abundance are the result of real change rather than background noise, using standard statistical routines (Haines-Young *et al.*, 2000). In addition, an environmental stratification provides a basis for stratified random sampling and enables samples to be placed consistently within the context of the entire continent, with robust statistical estimates and associated error terms. In contrast, studies which rely on expert judgement to select samples cannot be extrapolated statistically.

It is essential, however, that the environmental stratification has a sufficiently fine resolution and that it is derived statistically so that the strata are unambiguously determined by specific variables. The stratification is therefore reproducible and, as far as possible, independent of personal bias. This is of particular importance where large-scale continuous gradients are involved over thousands of kilometres, e.g. from Britain to Denmark, Sweden and Finland. No clear boundaries between zones are present in such cases, but statistical analysis provides robust divisions based on the balance between the variables that make up the database.

The need for statistical environmental stratification was first recognized by field ecologists at the *Institute of Terrestrial Ecology* (ITE) (now *Centre for Ecology and Hydrology* (CEH)) in the UK in the 1970s. These scientists realized that strategic stratified random sampling was the only feasible way of assessing ecological resources, such as habitats and vegetation, and enable monitoring schemes to be developed for large, heterogeneous areas (Bunce *et al.*, 1996abc ; Haines-Young *et al.*, 2000 ; Firbank *et al.*, 2003). Sheail & Bunce (2003) have recently described the history and development of environmental classification and strategic ecological survey in the UK. Several other countries and regions have also adopted quantitative classifications as the basis for survey, monitoring and management, e.g. Australia (Mackey *et al.*, 1988), Spain (Elena-Rosselló, 1997 ; Regato *et al.*, 1999), Austria (Wrbka *et al.*, 1999), New Zealand (Leathwick *et al.*, 2003ab), and Senegal (Tappan *et al.*, 2004).

Two earlier European statistical stratifications have been produced. In the first, Jones & Bunce (1985) defined 11 classes on a 50 km x 50 km grid for Europe. More than a decade later, improved data availability, software, and computing power, allowed the classification of 64 classes on a 0.5° grid (approximately 50 km x 50 km) (Bunce *et al.*, 1996d). Although this latter classification was used in a range of studies (Bunce *et al.*, 1996e ; Bunce *et al.*, 1997 ; Duckworth *et al.*, 2000 ; Petit *et al.*, 2001), the coarse resolution limited its application for ecological sampling. At this resolution, some of the grid cells are relatively heterogeneous for climate and altitude. For example, the grid cell with the Picos de Europa in the Cantabrian mountains in north-western Spain contains an elevation range from sea level to mountain summits at an altitude of 2500 m, with associated contrasting climate regimes. The classification was therefore too coarse to be used for monitoring programmes for land use change and for developing detailed scenarios.

Other European classifications with a higher resolution, e.g. maps of Potential Natural Vegetation (Bohn *et al.*, 2000 ; Noirfalise, 1987), biogeography (EEA, 2002) or ecoregions (Olson *et al.*, 2001) have classes that have not been defined statistically. They depend on the experience and judgement of the originators and rely upon the intuition of the observer in interpreting observed patterns on the basis of personal experience. These classifications, whilst important as descriptions of environmental regions, are not suitable for statistical stratification. Some bioclimatic classifications are quantitative and reproducible, e.g. those used in dynamic global vegetation modelling (Woodward & Rochefort, 1991 ; Prentice *et al.*, 1992). However, they distinguish too few classes at the European scale to provide suitable stratification for random sampling of ecological resources.

In this chapter an *Environmental Stratification of Europe* (EnS) is presented that has 84 strata with a 1 km^2 resolution. The stratification is based on statistical clustering, so that subjective choices are explicit, their implications are understood, and the strata can be seen in the context of Europe as a whole. By demonstrating this new stratification approach, and by making the EnS public, a tool is now available for European ecologists to use for stratified random sampling of ecological resources and the selection of sites for representative studies across the continent. The strata can also be used for modelling exercises, scenario development, and reporting.

Materials and methods

The construction of the *Environmental Stratification of Europe* has entailed three major stages (Fig. 5.1). (1) The selection of the relevant environmental variables. (2) The extraction of the main environmental gradients using Principal Components Analysis (PCA) and subsequent statistical clustering. (3) Post-processing to minimize isolated groups of grid cells. Finally, in order to give the EnS more credibility, the EnS is compared to other available classifications, and correlations with other environmental data are calculated. All spatial calculations were carried out using ArcGIS 8.2 (ESRI, 2002).

Selecting relevant variables

In order to determine which variables are best suited for stratification of the European environment, some form of conceptual model is needed. This must be a simplified model that includes the relation between abiotic and biotic components with ecological relevance. Fig. 5.2 shows such a conceptual model, based on work by Klijn & de Haes (1994), which creates a functional hierarchy between different ecosystem components (e.g. climate, soil, vegetation). The lower components are relatively dependant on higher components (downwardly directed arrow). For instance plant species are associated with specific soil conditions; major soil groups are formed under different climatic conditions. Furthermore, changes in the relatively independent higher components will have unavoidable influences on lower components (e.g. climate change will affect species distribution). Influences in the other direction are also recognised (upwardly directed arrow), but the model can be seen as a spatial and temporal hierarchy, with global, relatively stable component at the top.

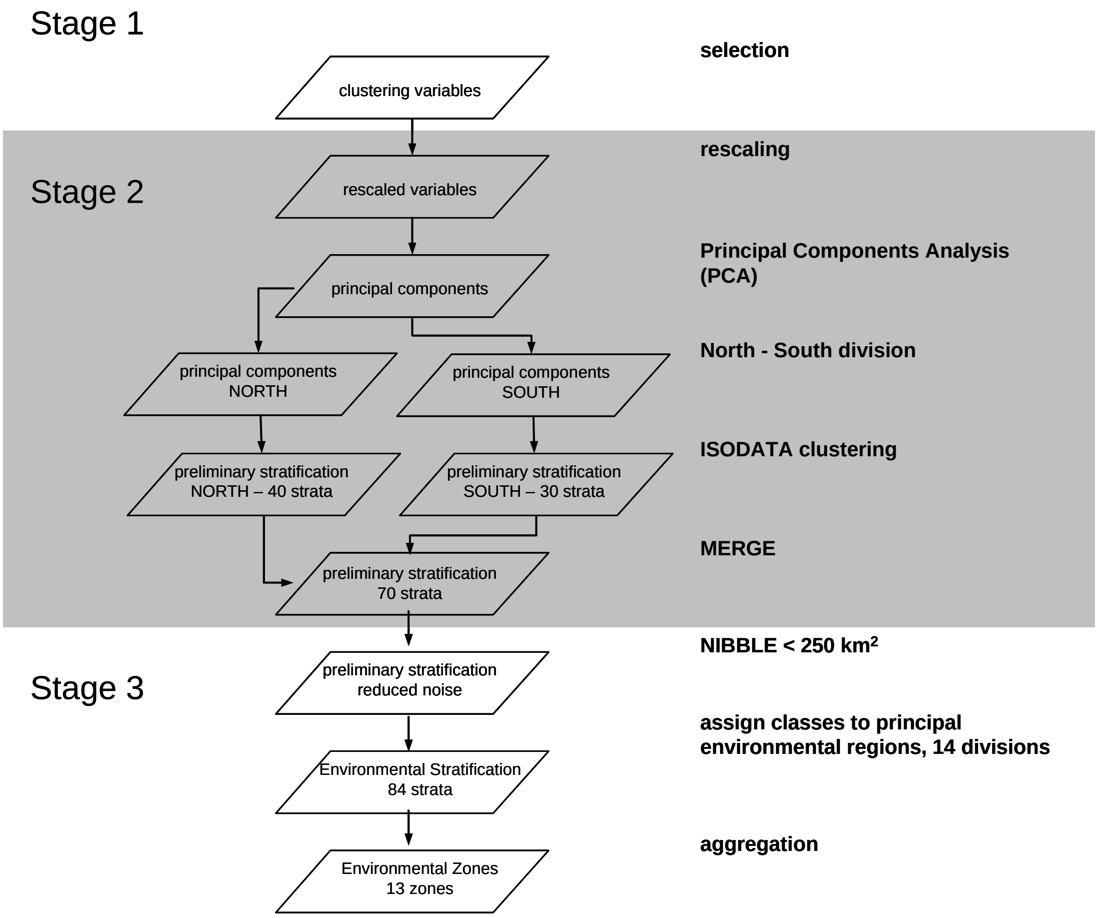

Figure 5.1. Flow chart of the creation of the Environmental Stratification in three major stages. (1) variable selection, (2) clustering of the selected variables into strata (3) some post-processing. All calculations were done in ArcGIS 8.2 (ESRI, 2002).

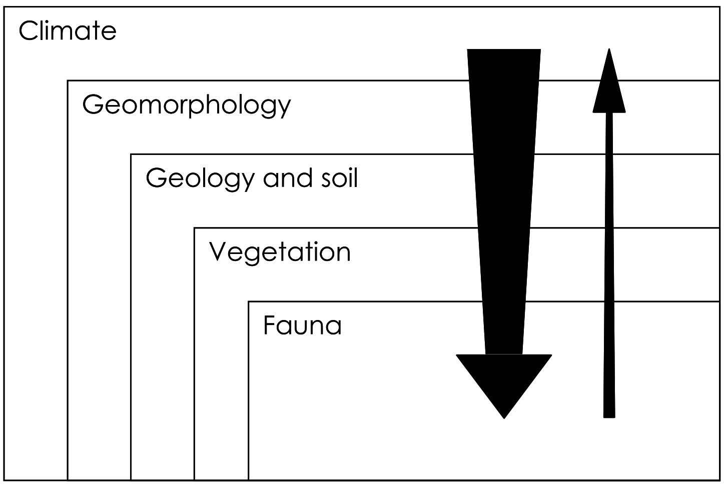

Figure 5.2. Conceptual model of an ecosystem, showing a hierarchy of relative dependence between major components (after Klijn & de Haes, 1994). In most cases, lower component in the hierarchy are relatively dependant on higher components, as indicated by the thickness of the arrows.

Others have also recognized the spatial hierarchy described in Klijn's model (Walter, 1973 ; Leser, 1976, 1991 ; Van der Maarel, 1976 ; Odum, 1983 ; Bailey, 1985 , 1987 ; Godron, 1994 ; Klijn & de Haes, 1994 ; Breckle & Walter, 2002). Walter (1973), for instance, distinguished climatic zonobiomes, and in mountainous regions orobiomes, determined by altitudinal steps. These biomes are conditional for the formations of soils, which usually show a more fine-grained pattern, with regional heterogeneity caused by for instance hydrological processes, erosion, or human activity (Breckle & Walter, 2002). Vegetation superimposes an even finer pattern of local variation, consisting of various succession stages and human land use. For example: zonobiome VI, with a temperate climate and short periods of frost, is associated with forest brown earths and grey forest soils. The natural climax vegetation, associated with this climate and these soil conditions is a nemoral broad-leaf-deciduous forest (Breckle & Walter, 2002).

Of course, at field level, there is large heterogeneity in environmental conditions, as well as land cover. Furthermore, there are feedbacks in the other direction (upwardly directed arrow in Fig. 5.2). For example vegetation also influences soil properties and can even influence local climate. Nevertheless, in the continental or global context, ecosystem patterns are caused by the above-mentioned hierarchy (Klijn & de Haes, 1994). Bunce *et al.* (1996a ; 2002) have shown that this hierarchy applies even on a national scale for large countries such as Great Britain and Spain. This hierarchy therefore is a suitable starting point for selecting relevant variables for creating a European environmental stratification.

Climate

The most comprehensive high-resolution climate dataset available for Europe is the CRU_TS1.2 (Mitchell *et al.*, 2004), developed by the *Climatic Research Unit* (CRU) at the *University of East Anglia*. It has a 10 arcmin x 10 arcmin resolution (approximately 16 km x 16 km) and contains monthly values for five variables during the period 1900-2000. Depending on the variable and year, between 200 and 1600 stations were interpolated using trivariate thin-plate spline surfaces, making use of a 1 km^2 elevation database as a co-predictor. The CRU_TS1.2 dataset is based on the CRU CL2.0, which contains global climatologies for 1969-1990 (New *et al.*, 2002), but is restricted to the 'greater European window' (11°W, 32°E, 34°N, 72°N) and uses an updated climate database. For the latter dataset generalized cross validation (GCV) was performed for different regions of the world. In Europe, the average predictive error for precipitation stations used in fitting the surface varies between 12 and 15% of the monthly rainfall, while prediction errors for mean monthly temperature range between 0.8 and 1.1°C. (New *et al.*, 2002).

Hutchinson & Gessler (1999) give a good description on the methodology used for fitting climate surfaces.

The dataset used, CRU_TS1.2, contains mean monthly values for temperature, precipitation, percentage sunshine, vapour pressure, and daily temperature range. From the daily temperature range and the mean temperature, the average minimum and average maximum temperature can be calculated. From the total dataset, 1971-2000 climatologies were calculated as 30-year averages.

The 10 arcmin x 10 arcmin resolution, whilst nine times more detailed than the earlier ITE classification on a 0.5° grid (Bunce *et al.*, 1996d), is still coarse, especially for sampling 1 km^2 squares. Meanwhile, at the local level, environmental patterns are relatively independent of wider climate patterns and are dependant on local topography (Bunce *et al.*, 1998). The climate parameters were therefore resampled from the 10 arcmin x 10 arcmin grid of the CRU_TS1.2 dataset in a 1 km^2 grid, for which topographic data are available. From the resampling techniques available in ArcGIS, bilinear interpolation was chosen to best represent climatic gradients between grid cells. This downscaling procedure ignores elevation as a co-predictor. As a result, excess smoothing of the climate variables occurs in grid cells which are heterogeneous in elevation, resulting in some inaccuracies in the final stratification. In part this is counteracted by inclusion of high-resolution elevation data (next section). In stratified sampling exercises these inaccuracies will be reflected in the standard errors of the sample mean (see Discussion).

To reduce the computational load it was necessary to select a subset of the total available data (7 variables x 12 months). For this purpose, in the earlier ITE classification, a thorough statistical analysis was carried out (Bunce *et al.*, 1996d) leading to the selection of 15 variables. In the present project a comparable set of variables was selected from the total available data (Table 5.1). In order to reflect the overall seasonal climate variation, data were selected for four months in the year, January, April, July and October. This was done for the four available variables that were closest to those used in the 1996 ITE classification, namely mean monthly minimum and maximum temperature, precipitation, and percentage sunshine. Table 5.1 lists the variables of the original ITE classification and the EnS.

Table 5.1. A comparison between the variables selected for the *Environmental Stratification of Europe* (EnS) and the ITE classification (Bunce *et al.*, 1996d). The variables represent mean monthly values for each grid cell. For the EnS slope and altitude data are from the HYDRO1k dataset (http://edcdaac.usgs.gov/gtopo30/hydro/) and the climate data from CRU TS1.2 (Mitchell *et al.*, 2004). The ITE classification used an earlier CRU dataset (Hulme *et al.*, 1995).

EnS (1km² resolution)	ITE classification (0.5° x 0.5° resolution)
Altitude	Maximum altitude
	Mean altitude
	Minimum altitude
Slope	
Northing (latitude)	Northing (latitude)
Oceanicity	Oceanicity
Minimum temperature January	
Minimum temperature April	
Minimum temperature July	Frost days in July
Minimum temperature October	Frost days in November
Maximum temperature January	
Maximum temperature April	
Maximum temperature July	Maximum temperature in September
Maximum temperature October	Maximum temperature in October
Precipitation January	Rain days in December
Precipitation April	
Precipitation July	Precipitation in June
Precipitation October	Precipitation in October
Precipitation in November	
	Rain days in November
Percentage Sunshine January	
Percentage Sunshine April	Sun hours in May
Percentage Sunshine July	Sun hours in June
Percentage Sunshine October	
	Wind speed in April

Geomorphology

Geomorphology encompasses the formation and shapes of landforms, e.g. alluvial flats and alpine valleys. No consistent European geomorphological map exists. However, detailed digital elevation models (DEMs) are available, which convey a high proportion of the information required, i.e. altitude and slope. These data act as surrogates for geomorphological information. The best dataset available is the *United States Geological Survey* (USGS) HYDRO1k global digital elevation model, with a resolution of 1 km². It was created by projecting the USGS GTOPO30 dataset, which has a 30 arcsec resolution, onto an equal area Lambert Azimuthal projection. Slope, aspect, and flow properties were also calculated for the dataset. HYDRO1k is distributed by the *Land Processes Distributed Active Archive Center* (LP DAAC), located at the USGS EROS Data Center (http://lpdaac.usgs.gov).

Oceanicity and northing

In the ITE classification northing, in the form of latitude, as well as oceanicity were included. By including northing in the stratification, differences in day-length and radiation are incorporated as well as a degree of locational information. Oceanicity expresses the buffering influence of the ocean, resulting in cooler summers, milder winters, and a lower degree of interseasonal variability. In the ITE classification oceanicity was defined by climatic criteria as the mean annual temperature range adjusted for latitude, as recommended by CRU. In the EnS, oceanicity was defined as the July - January temperature range divided by the sine of the latitude. Large mean annual temperature ranges (20-25°C) are found in Eastern Europe, small ranges on the Atlantic coast (10-15°C). Because the relative influence of the annual temperature range differs from north to south, the indicator is divided by the sine of the latitude.

Geology and soil

An investigation was conducted to assess whether it would be possible to include some geological or soil variables into the stratification. Known landscape patterns resulting form soils and geology (e.g. fluvial deposits and peat formations) are not present in a stratification based on bioclimatic variables alone, although there will be strong associations. For example, all permafrost soils are in arctic and alpine climates, podzols are predominantly found in boreal climates, and forest brown earths in temperate climates (Breckle & Walter, 2002).

Unfortunately, currently no European geological map is available and the available soil maps are difficult to include in statistical clustering due to the classification method that is used for mapping soils: it is based on expert knowledge of soil scientists, without specified critical thresholds. Furthermore, the higher aggregation levels do not show an equal distribution of soil properties. Whilst these groups provide a sound descriptive base, they are of limited value in statistical analysis. A second problem arises because soil maps contain nominal data, which are not easily incorporated into the statistical clustering that is based on continuous data. Transformation is possible, but results in individual vectors for each soil type, which would unbalance the final set of variables, as discussed by Bunce *et al.* (1996a). Finally, soil variables derived from pedo-transfer functions (e.g. pH and water holding capacity) can be incorporated into the clustering, but because the climate variables vary at a broader scale than the soil variables, the resulting map is fragmented and shows little internal consistency and little relation to climate zones. In principal, this could be overcome by weighing the soil variables down to allow broader scale climate to remain dominant (cf Belbin, 1991). However, considering inconsistencies in the soil data, and the lack of experience in assigning weights to the soil properties, it was decided not to include soil information in the stratification. Detailed regional soil information could eventually prove valuable in deriving local strata (see Discussion).

The variables selected

The variables selected are comparable to those used in the original ITE classification (Table 5.1), although the original statistical selection procedure for the climate variables was not repeated. As Bunce *et al.* (2002) have shown, using the European ITE classification, two British and one Spanish classification, the core patterns of statistical environmental classifications are stable regardless of details pertaining to the variables and algorithms used. Differences in detailed strata distribution are likely to occur along large-scale continuous gradients where no clear boundaries are present (e.g. from Britain to Demark, Sweden and Finland). However, such differences will have minimal impact in any estimates derived from the strata, because the gradient in ecological parameters will also be continuous and relatively homogeneous over large distances.

Running the classification

PCA allows redundant data to be compacted into fewer dimensions that are non-correlated and independent and are often more readily interpretable than the source data (Faust, 1989 ; Jensen, 1996). The *ERDAS IMAGINE field guide* (ERDAS, 1997), accessible on the internet, gives a clear description of the process. In ArcGIS, PCA is carried out on the matrix of covariances between the variables, implicitly centring and standardizing by the input variables, as required when analysing variable that are measured in different units (Jongman *et al.*, 1995). In order to reduce file size and increase calculation speed, the variables were converted integers with a 0 – 10,000 range.

The Iterative Self-Organising Data Analysis Technique (ISODATA) (Tou & Conzalez, 1974) was used to cluster the principal components into environmental strata. This technique is widely used in image analysis fields, such as remote sensing and medical sciences, e.g. Banchmann *et al.* (2002) ; Pan *et al.* (2003). ISODATA is iterative in that it repeatedly performs an entire classification and recalculates statistics. Self-organizing refers to the way in which it locates clusters with minimum user input. The ISODATA method uses minimum Euclidean distance in the multi-dimensional feature space of the principal components to assign a class to each candidate grid cell. The process begins with a specified number of arbitrary cluster means. The (Euclidian) environmental distance between the candidate grid cell and each cluster mean is calculated. The grid cell is then allocated to the cluster whose centroid is the closest. The iterations are terminated when percentage of grid cells whose assignments are unchanged reaches 100%. The ITE classification distinguished 64 strata using an arbitrary stopping rule. In the new stratification, classification into 70 strata was chosen, a number which makes characterisation of the strata feasible.

The original ITE classification showed that the Mediterranean region is distinct from northern Europe. When the clustering was first performed a relatively large number of small strata were present in the Mediterranean region and several large strata in northern Europe. Many strata (>120) would be needed to divide northern Europe, creating too many strata for practical purposes overall. This problem was solved by using a step-wise procedure to divide Europe in two zones, based on a PCA of the climate variables and clustering into two classes. The northern class covers 70% of Europe and the southern (Mediterranean) class covers 30%, as shown in Fig. 5.3. The division is comparable to that of the original ITE classification, with only minor differences in the northern boundaries, and it also close to the divisions described by Kendrew (1953). In the next stage of the analysis, the principal components of the full set of variables were used to classify northern and southern Europe separately. Northern Europe was clustered into 40 strata and southern Europe into 30 strata. In this way, environmental heterogeneity in northern Europe is emphasized, while recognizing the greater variability in the Mediterranean region. Compared to the northern class, it has almost 50% (30/70) of the number of strata, but only covers 30% of the spatial extent.

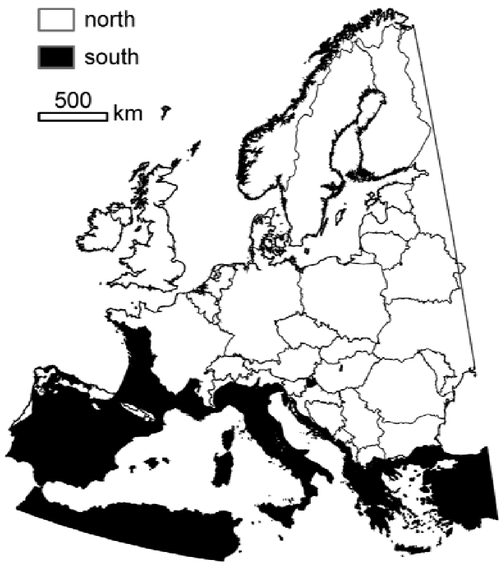

Figure 5.3. The European environment was classified into two classes, northern and southern Europe, based on ISODATA clustering of the first three principal components of only the climate variables. National borders are indicated for reference purposes.

Post-processing

In the original map of the environmental strata, there is a dispersed scatter of small regions of only a few square kilometres. For most applications, such fragmentation is not useful on a European scale. Therefore, all regions smaller than 250 km^2 were identified and assigned to the strata of the neighbouring grid cells. This procedure eliminates most of such noise, much improving the clarity of the map, but simultaneously introducing a bias that could lead to higher statistical errors in sample means. The procedure of removing noise is analogous to the use of the discriminant function procedure in the original ITE classification. The original output is also available, for studies that require such level of detail.

In some cases EnS strata occurred in two distant regions, e.g. in the Atlantic as well as Adriatic regions. Climatically these regions are indeed comparable, but they are very different in biogeography, and therefore species composition. As a consequence, sampling these strata for habitats, vegetation, and landscapes would produce estimates with large standard errors. Furthermore, aggregation and naming of the strata would be extremely complicated. For these reasons all strata were assigned to one of six main environmental regions: Alpine, Boreal, Continental, Atlantic, Mediterranean and Anatolian. Strata that occurred in two such regions were separated. Arguably, for some applications this division is not desirable. For instance, the original strata could be used as an explanation of similar vegetation structure in distant regions. For this reason the original 70 strata are also available in the EnS dataset.

Relation to other datasets

In order to give the EnS more credibility, both to the scientific community, as well as to policy advisors, it is important to show its relation to other widely used European datasets. This was done in three ways: (1) By comparing the EnS to other classifications. (2) By assessing correlations between the EnS and other datasets. (3) By describing the EnS strata with other available data. Some important properties of the datasets used in this chapter summarized in Table 5.2.

Comparison

As mentioned in the introduction, several classifications of the European environment exist that are not appropriate for stratified sampling in the field due to their spatial resolution (the ITE classification), the limited number of classes that are distinguished (biomes) or ambiguous definitions of class boundaries (e.g. WWF ecoregions). Although these classifications are not suitable for statistical sampling, there are many similarities in the environmental patterns detected by these classifications and the EnS. To test these similarities, the strength of agreement between the EnS and three other available datasets was determined by calculating Kappa statistics (Monserud & Leemans, 1992). This is identical to the approach used by Lugo *et al.* (1999) to 'verify and evaluate' their classification for the United States.

For the Kappa analysis the datasets that are compared must have the same spatial resolution, and distinguish the same classes. To meet these requirements the EnS was resampled to the resolution of the alternative classification and the two classifications were clipped to the largest overlapping extent. A contingency matrix was calculated to determine the best way to aggregate the EnS strata to the classes of the alternative classification. Kappa could then be calculated using the default settings of the Map Comparison Kit (Visser, 2004). The three alternative classifications used in this comparison were: the ITE classification (0.5° resolution, 64 classes (Bunce *et al.*, 1996d)) ; global biomes determined by the IMAGE model for 1990 (0.5° resolution, nine classes (IMAGE team, 2001)) ; WWF ecoregions (polygons resampled to 1 km^2, 28 classes (Olson *et al.*, 2001)).

Correlation

Based on the conceptual hierarchy used to determine the variables used to construct the EnS (Fig. 5.2), the EnS should show correlations with other environmental datasets, including those lower in the conceptual hierarchy, e.g. those for soil, vegetation, species distributions. Even European land cover maps can be expected to correlate with the EnS, after all, the distribution of several principal land cover types (e.g. *coniferous forest*, *deciduous forest*, *rain fed cropland*, *vineyards*) are determined by broad climatic patterns.

For quantitative variables (e.g. length of the growing season, soil pH), with a ratio or interval data scale, the correlation was calculated between the mean score of the first principal component of the classification variables, and the response variable.

For nominal environmental datasets (e.g. those for Potential Natural Vegetation, soils, and land cover), it is necessary to calculate a multivariate proxy that indicates the association of the various classes in the dataset with each EnS stratum. This was done by determining the area-percentages of each nominal class (e.g. soil type) within each EnS stratum. For example, Boreal EnS strata are expected to score high values for the podzol soil types, but low scores for Mediterranean brown earths. From this multivariate dataset, the first principal component is calculated for each EnS stratum, using the default settings in SPSS (SPSS, 2001). This result can then act as the required proxy, and can be correlated with the mean first principal component of the classification variables.

For binary species distribution datasets, detrended correspondence analysis (DCA) can be used to analyse inherent gradients in the dataset (Hill & Gauch, 1980). The default settings of CANOCO (Braak ter & Šmilauer, 1998) were used to calculate the first DCA axis, which was then correlated with the mean first principal component of the classification variables.

Description

Finally, for each stratum, zonal statistics were calculated for the variables on which the stratification is based. These statistics help understand stratum boundaries and give a general description of the strata. Box plots can be used to summarize the spread of values in each stratum. Other environmental datasets (i.e. soil, potential natural vegetation, and land cover) provide a more complete description of the strata.

Results

The *Environmental Stratification of Europe*

The first three principal components (Fig. CP10) explain 88% of the variation in the 20 input variables. The subsequent two-tier clustering procedure produced 70 classes. Regions smaller than 250 km^2, less than 0.12% of the total extent, were identified and assigned to neighbouring strata. In 14 cases a class occurred in two distant environmental regions. In these cases the classes were split, resulting in a final stratification of 84 strata.

The 84 EnS strata provide a convenient set for a continent as diverse as Europe and are appropriate for stratified sampling and analysis of environmental data. However, there are too many strata for summary reporting and presentation of the principal characteristics of Europe. An aggregation of the strata into a limited number of Environmental Zones (EnZs) was created to facilitate communication, based on the experience of a similar situation in Great Britain where 32 land classes were reduced to six zones for reporting purposes. The main environmental regions mentioned above (Alpine, Boreal, Continental, Atlantic, Mediterranean and Anatolian) were subdivided on the basis of the mean first principal component score of the strata in the regions. In order to distinguish the Mediterranean Mountains zone (MDM), an extra rule was required. All Mediterranean strata with altitudes above 1000 m were assigned to MDM. The remaining southern strata were assigned to Mediterranean North (MDN) or South (MDS) based on mean first principal component scores of the strata.

Table 5.2. Summary of datasets that were available to compare (a) and correlate (b) with the EnS. While it is impossible to discuss the quality of these datasets at length, this table gives insight in to the spatial scale, data scale and extent of the datasets. The number of classes or types distinguished by the datasets gives further insight into the level of detail provided by the datasets.

(a)

Dataset	**Reference**	**Spatial scale**	**Data scale**	**Extent**	**Number of classes in Europe**
IMAGE 1990 biomes	IMAGE-team, 2000	0.5°	nominal	World	9
WWF ecoregions	Olson *et al.*, 2001	? 1: 5 000 000	nominal	World	23
ITE European land classification	Bunce *et al.*, 1996d	0.5°	nominal	European window	64

(b)

Dataset	**Reference**	**Spatial scale**	**Data scale**	**Extent**	**Number of types in Europe**
Atlas Flora Europea - *Quercus* species	Jalas & Suominen, 1976	50km	binary	Pan-Europe	25 species
CORINE land cover	EEA, 2000	250m	nominal	European Union (15)	44 types
PELCOM land cover	Mücher *et al.*, 2001	1km	nominal	Pan-Europe	14 types
Potential Natural Vegetation	Bohn *et al.*, 2000	1:2 500 000	nominal	Pan-Europe	740 types
FAO Digital Soil Map of the World	FAO, 1991	1:5 000 000	nominal	World	345 types at level 3
FAO Agro-ecological Zones	FAO/IIASA, 2000	5 arcmin	nominal	World	7
HYDRO1k DEM and slope	[http://edcdaac.usgs.gov/]	1km	ratio	World	not relevant
CRU TS1.2 climate	Mitchell *et al.*, 2004	10 arcmin	interval / ratio	European window	not relevant
MARS agronomic variables	[http://agrifish.jrc.it]	50km	ratio	Pan-Europe	not relevant
IGBP soil variables	Global Soil Data Task, 2000	5 arcmin	interval / ratio	World	not relevant

Consistent naming is important to emphasise the statistical approach and prevent misleading interpretations. The EnZs have, therefore, been ordered by the mean value of the first principal component of the classification variables, which expresses the north-south environmental gradient across Europe. In the same way, the EnS strata that fall within the EnZs are also numbered by the mean value of the first principal component. The EnS strata have been given systematic names based on a three letter abbreviation of the EnZ to which the stratum belongs, and an ordered number based on the mean first principal component score. For example, the EnS stratum with the highest mean first principal component score within the Alpine North EnZ is named ALN1 (Alpine North one). The Environmental Stratification can now be mapped by colouring the EnS strata according to their EnZ and labelling them with their consistent names, as shown in Fig. CP11. Since a numerical label is sometimes more convenient, all EnS strata are also numbered based on first principal component score.

Relation to other datasets

Comparison

Table 5.3 shows that the Kappa values for the comparison of the EnS with available datasets range between 0.55 and 0.72, indicating 'good' or 'very good' comparisons, according to Monserud & Leemans (1992). The Kappa values are higher than those reported by Bunce *et al.* (2002) in a comparison of biogeographical classifications of Europe.

Table 5.3. Strength of agreement, expressed by the Kappa statistic, between the EnS and three other European classifications. Monserud & Leemans (1992) gave an indication of the quality of the comparison for different ranges of Kappa.

Dataset	Kappa	Quality of the comparison
ITE classification	0.55	good
1990 IMAGE biomes	0.72	very good
WWF ecoregions	0.6	good

Correlation

Fig. 5.4 and Table 5.4 show that all datasets available show a significant correlation with the EnS (Pearson correlation coefficient at the 0.01 level). Especially for the land cover maps (CORINE and PELCOM) a considerable amount of the variation is not explained by the EnS. This is not surprising for two reasons: (1) These datasets include broad categories that do not differentiate across the European environment. For instance, categories such as pastures, coniferous forest, and shrubland, occur across Europe as one category, while in the field there are differences in the species composition of the vegetation. (2) Land cover is directly influenced by human decisions that do not necessarily follow regional patterns. For instance, in the vicinity of Newmarket (East Anglia, eastern England) the predominance of racing stables has resulted in several square kilometres of grassland in a region otherwise dominated by crops.

Figure 5.4. Significant correlations were found between the mean first principal component of the classification variables per EnS stratum and available ecological datasets, using Pearson's correlation coefficient at the 0.01 level. Binary and nominal data cannot be directly correlated to the principal component scores, therefore orthogonal regression and Detrended Correspondence Analysis (DCA) were used for nominal and binary data respectively (see section Material and methods for details). The statistics were calculated for the European part of the stratification, since this is the area of interest and some datasets used for comparison do not cover northern Africa. Table 5.2 gives a summary of the datasets. (a) Potential Natural Vegetation (Bohn *et al.*, 2000). (b) *Quercus* species in the *Atlas Flora Europea* (Jalas & Suominen, 1976). (c) CORINE land cover (EEA, 2000).

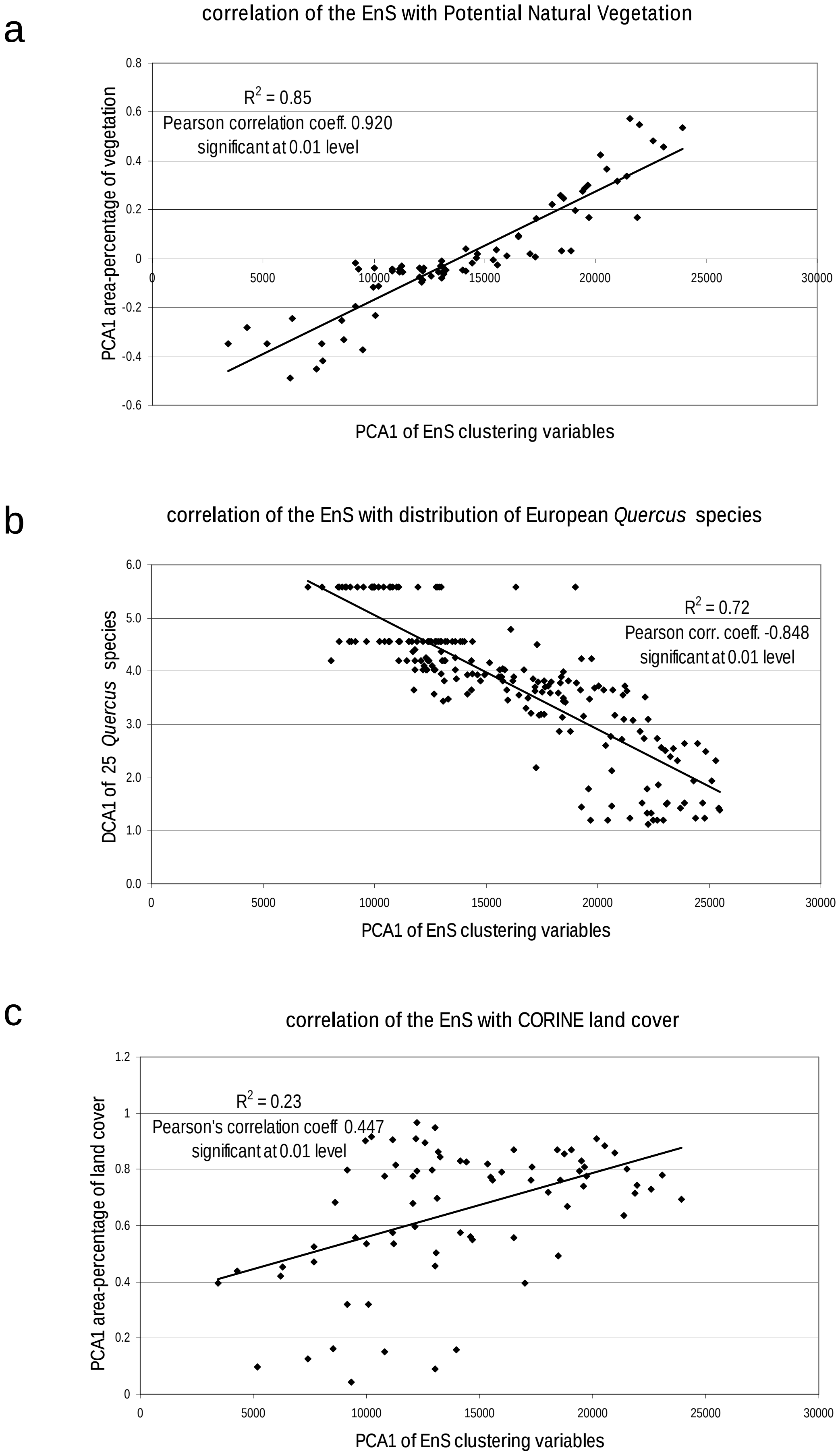

Figure 5.4. See previous page for detailed caption.

Table 5.4. Significant correlations were found between the mean first principal component of the classification variables per EnS stratum and available ecological datasets, using Pearson's correlation coefficient at the 0.01 level. Binary and nominal data cannot be directly correlated to the principal component scores, therefore orthogonal regression and Detrended Correspondence Analysis (DCA) were used for nominal and binary data respectively (see section Material and methods for details). The statistics were calculated for the European part of the stratification, since this is the area of interest and some datasets used for comparison do not cover northern Africa. Table 5.2 gives a summary of the datasets used in this analysis. Fig. CP11 shows the regressions of three datasets.

Dataset	**Data scale**	**Reference**	**R^2 of the regression**	**Pearson's correlation coefficient**
MARS annual temperature sum	ratio	[http://agrifish.jrc.it]	0.95	0.978
Potential Natural Vegetation	nominal	Bohn *et al.*, 2000	0.85	0.92
MARS growing season (# days >=5°C)	ratio	[http://agrifish.jrc.it]	0.83	0.911
Quercus species distribution	binary	Jalas & Suominen, 1976	0.72	-0.848
DSMW, all soil types	nominal	FAO, 1991	0.59	0.771
IGDP soil pH first 100cm	interval	Global Soil Data Task, 2000	0.59	0.768
Agro-Ecological Zones	nominal	FAO/IIASA, 2000	0.45	0.671
DSMW, main soil groups	nominal	FAO, 1991	0.43	0.659
IGDP soil organic carbon first 100cm	ratio	Global Soil Data Task, 2000	0.42	-0.652
PELCOM land cover	nominal	Mücher *et al.*, 2001	0.34	0.585
CORINE land cover	nominal	EEA, 2000	0.23	0.477

Description

The EnS is a multivariate stratification. The strata show overlapping ranges for most variables because the differences between them are multidimensional. Nevertheless, description of the strata with available datasets helps to understand the division of the strata. Each stratum has been described using the datasets listed in Table 5.2. An example of such a description for the mean maximum July temperature is given in Fig. 5.5.

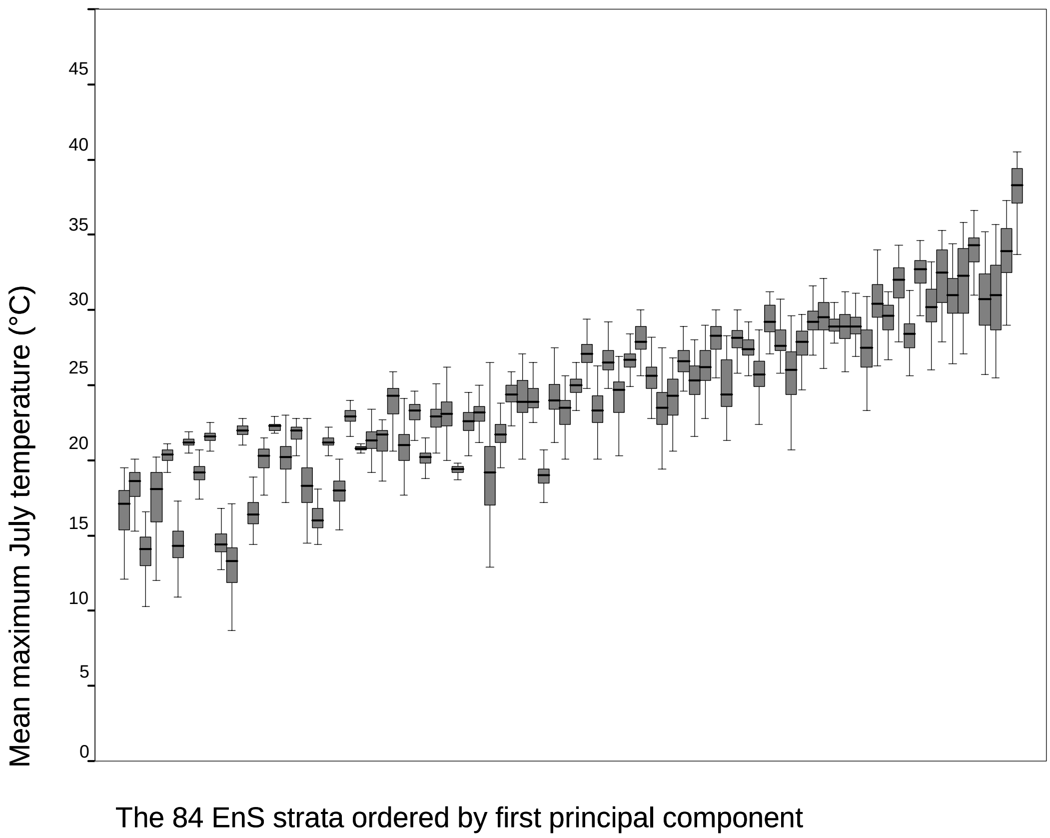

Figure 5.7. Box plots of the mean maximum temperature in July summarize the spread of the variable in each stratum. The strata are ordered by the mean value of the first principal component for each EnS stratum, which depicts the north-south environmental gradient across Europe. The climate data were derived from the CRU_TS1.2 dataset (Mitchell *et al.*, 2004).

Discussion

Quality of the stratification

The aim of the *Environmental Stratification of Europe* is to form a sufficiently detailed statistical stratification of Europe's environment that can be used for strategic random sampling and for the comparison and analysis of diverse ecological spatial data. Taking into account the functional hierarchy in ecosystem components, discussed before, it is appropriate to construct an environmental stratification for Europe using mainly climatic variables. In order for the stratification to be functional, it should show sufficient detail and it should correlate well with ecological data. Keeping these requirements in mind, it follows that it should be possible to select the best stratification from a suite of possible candidates, based on different variables and clustered into different numbers of strata and then choosing the stratification which holds the highest correlation with independent ecological datasets. This was the approach that had originally been envisaged, but it was not followed for several reasons. Firstly by not being able to incorporate soil variables, possible combinations of variables were reduced. Secondly, it proved difficult to obtain ecological datasets to correlate with the stratification. However, as Bunce *et al.* (2002) have shown, statistical environmental classifications will have much in common and decisions between them are arbitrary anyway and judgement is not involved in determining boundaries between the strata. Finally, in practice there is a limitation to the number of strata that are convenient to handle, analyse and describe.

The analyses of the EnS with available datasets, cannot be seen as a true validation of the stratification, but do indicate that the EnS forms an appropriate stratification of environmental variability in Europe. The comparisons with other classifications are good (Table 5.3), considering that two of the classifications (the WWF ecoregions and the IMAGE biomes) were constructed from different perspectives. Furthermore, the significant correlations between the EnS and various ecological data (Table 5.4 and Fig. 5.4), justify its wider application. The final test is through the application of the strata to field survey and the subsequent derivation of estimates and correlations.

The data used in the present study have limitations, but are the best available at the current time. Future improvements in data layers, when available, could improve the efficiency of the stratification. However, the comparisons with available classifications, as described above, show that the main environmental boundaries in the Europe are relatively stable. It is therefore likely that any changes in the boundaries will affect the eventual estimates only to a small degree. Instability of the classified strata due to misclassification is discussed in Bunce *et al.* (1996ab), where the clustering procedure had to be carried out in two stages. In the present study such instabilities were overcome by classifying all 1 km^2 sample squares in a single analysis. Any change in the databases used for classification, or in the classification procedure, will cause some squares to change class, but will not alter the overall pattern. However, any inefficiencies of the stratum will eventually be incorporated in the standard errors attached to the field estimates (Firbank *et al.*, 2003).

In mountainous regions steep environmental gradients occur over short distances. Although the EnS picks up these gradients more accurately than the ITE classification, it still shows insufficient detail in most mountainous strata to form a good basis for defining distributions of predicted parameters at a lower level. The stratum ALS1 (Alpine South one) for instance covers a range of altitude from 630 m – 4453 m. This lack of detail can be solved with an algorithm dividing all mountainous strata into three substrata that are equal in area, e.g. ALS1-high, ALS1-mid and ALS1-low. These strata are named Altitude Environmental Strata (AEnS). AEnS strata created for the Alps distinguish valleys, slopes and mountain summits. Although the method of creating AEnS strata is arbitrary, it offers a consistent division of mountainous strata, as is required for definition at a regional level (Jongman *et al.*, 2005). Alternatively, more detailed regional stratifications could be used to disperse samples within an EnS stratum, e.g. based on regional information about geomorphology, soils, or hydrology. As long as the samples are randomly dispersed, they can still be aggregated to the European context using the EnS.

While the 1 km^2 resolution may be considered coarse within Alpine environments, variation at lower resolutions can only be determined by field survey using procedures described by Firbank *et al.* (2003) for standardized sampling of, among others, vegetation, linear and freshwater features. Furthermore, all major monitoring exercises in the Alpine region, e.g. Wrbka *et al.* (1999) have also used 1 km^2 samples, supported by field survey.

A hierarchical framework and its applications

The procedure described by Bunce *et al.* (1996a) for the GB land classification uses the first principal component in to construct a hierarchy, but it was not as deterministic as the aggregation approach used in creating the EnS, which is entirely rule-based. The 84 EnS strata have been aggregated into 13 Environmental Zones, and even into seven generic Environmental Regions, but the EnS strata can also be disaggregated into approximately 200 AEnS strata. This hierarchical framework will allow for aggregation of local data into a European context. Alternatively it can be used to disaggregate regional data, as Petit *et al.* (2001) have shown for the distribution of habitats in Europe. In addition, different aggregations of the strata are possible to suit specific objectives. For instance, the EnS strata have been aggregated into European mountain zones for analysis European transhumance systems (Bunce *et al.*, 2004), and into principal biomes to aggregate global change impacts (Chapter 4 ; Metzger *et al.*, 2005).

The EnS is currently used within the EU 5th Framework project BioHab (Coordination of Biodiversity and Habitats in Europe) to provide the stratification for a framework for consistent monitoring of the occurrence and distribution of habitats in Europe (Bunce *et al.*, 2005). The EU 5th Framework project *Advanced Terrestrial Ecosystem Analysis and Modelling* (ATEAM) has used the EnZs as a basis for summarizing and comparing outputs from a suite of global change impacts models (Metzger *et al.*, 2004 ; available on the CD-ROM annex). Smith & Bunce (2004) have also used the strata from the Atlantic zone to estimate the number of veteran trees by field survey of over 90 1-km^2 samples. Other parallel examples quoted in the present paper, e.g. (Haines-Young *et al.*, 2000) have shown that the EnS would be appropriate for the assessment of ecological resources and change. A range of modelling exercises involving the assessment of consequences resulting from environmental change, e.g. Petit *et al.* (2001), scenario testing and modelling change, e.g. Parry *et al.* (1996) and Ewert *et al.* (2005) have also been conducted. The application of the EnS to other comparable studies is currently under discussion.

Conclusion

The *Environmental Stratification of Europe* has been constructed using tried-and-tested statistical procedures and shows significant correlations with principal European ecological datasets. As shown in comparative studies, such a stratification can be used for strategic random sampling for resource assessment, for the measurement of change and for modelling. The hierarchy of the EnS framework allows regional applications to be aggregated into continent wide assessments, thus facilitating the growing demand for coherent European ecological data to assist EU policy and global state of the environment assessments such as the EU *State of the Environment Report* and the *Millennium Ecosystem Assessment*. The EnS will not replace existing classifications, but will provide a framework for integration between them and subsequent estimates of habitat and vegetation when field data become available. The EnS is available on the CD-ROM annex to this thesis.

References

Bailey RG (1985) The factor of scale in ecosystem mapping. Environmental Management 9: 271-276.

Bailey RG (1987) Suggested hierarchy of criteria for multi-scale ecosystem mapping. Landscape and Urban Planning 14: 313-319.

Banchmann CM, Donato TF, Lamela GM, Rhea WJ, Bettenhausen MH, Fusina RA, Bois KR du, Porter JH, Truitt BR (2002) Automatic classification of land cover on Smith Island, VA, using HyMAP imagery. IEEE Transactions on Geoscience and Remote Sensing 40: 2313-2330.

Belbin L (1991) PATN technical reference manual. Division of Wildlife & Ecology, Commonwealth Scientific, Industrial, and Research Organization, Canberra, Australia.

Bohn U, Gollub G, Hettwer C (2000) Karte der natürlichen Vegetation Europas: Maßstab 1:2.500.000. Bundesamt für Naturschutz, Bon-Bad Godesberg, Germany.

Braak CJF ter, Šmilauer P (1998) CANOCO Reference Manual and User's Guide to Canoco for Windows: Software for Canonical Community Ordination (version 4). Microcomputer Power, Ithaca, New York, USA.

Breckle SW, Walter H (2002) Walter's Vegetation of the Earth: the ecological systems of the geo-biosphere, 4th edn. Springer, Berlin, Germany.

Bunce RGH, Barr CJ, Clarke RT, Howard DC, Lane AMJ (1996a) Land classification for strategic ecological survey. Journal of Environmental Management 47: 37-60.

Bunce RGH, Barr CJ, Clarke RT, Howard DC, Lane AMJ (1996b) ITE Merlewood Land Classification of Great Britain. Journal of Biogeography 23: 625-634.

Bunce RGH, Barr CJ, Gillespie MK, Howard DC (1996c) The ITE Land Classification: providing an environmental stratification of Great Britain. Environmental Monitoring and Assessment 39: 39-46.

Bunce RGH, Watkins JW, Brignall P, Orr J (1996d) A comparison of the environmental variability within the European Union. In: Jongman RHG (ed) Ecological and landscape consequences of land use change in Europe European Centre for Nature Conservation, Tilburg, The Netherlands, pp 82-90.

Bunce RGH, Watkins JW, Gillespie MK (1996e) The Cairngorm environment in a European context and the potential for change. Botanical Journal of Scotland 48: 127-135.

Bunce RGH, Watkins JW, Gillespie MK (1997) A stratification system for gathering agricultural and environmental data from different sources in the EU. In: Laurent C, Bowler I (eds) CAP and the regions: building a multidisciplinary framework for the analysis of the EU agricultural space Institut National de la Recherche Agronomique, Paris, France, pp 187-196.

Bunce RGH (1998) A framework for the analysis of cultural landscapes in Europe. In: Kovár P. (ed) Nature and culture in Landscape Ecology. Proceedings of the CZ-IALE conference 'Present and Historical Nature-Culture Interactions in Landscapes' Prague, 7-13 September 1999. The Karolinum Press, Prague, Czech Reublic, pp 69-73.

Bunce RGH, Carey PD, Elena-Rosselló R, Orr J, Watkins JW, Fuller R (2002) A comparison of different biogeographical classifications of Europe, Great Britain and Spain. Journal of Environmental Management 65: 121-134.

Bunce RGH, Pérez Soba M, Jongman RHG, Gómez Sal A, Herzog F, Austad I (eds) (2004) Transhumance and Biodiversity in European Mountains. Report from the EU-FP5 project Transhumount (EVK2-CT-2002-80017). IALE Publication series nr 1. Alterra, Wageningen UR, Wageningen, The Netherlands.

Bunce RGH, Groom GB, Jongman RHG, Padoa-Schippa E, Bogers M, Blust G de, Brandt J, Elena-Rosselló R, Hofer G, Ispikoudis I, Kovář P, Metzger M, Mücher C, Paelinckx D, Palo A, Perez-Soba M, Ramos I, Roche P, Pasta S, Peterseil J, Skånes H, Wrbka T (2005) Handbook for Surveillance and Monitoring of European Habitats. 1st Edition. Alterra Wageningen UR, Wageningen, The Netherlands.

Cochran WG (1977) Sampling techniques, 3rd edition. John Wiley & Sons, New York, USA.

Duckworth JC, Bunce, RGH, Malloch AJC (2000) Vegetation gradient in Atlantic Europe: The Use of Existing Phytosociological Data in Preliminary Investigations on Potential Effects of Climate Change on British Vegetation. Global Ecology and Biogeography 9: 197-199.

EEA (2000) CORINE land cover technical guide - Addendum 2000, Rep. No. 40. European Environment Agency, Copenhagen, Denmark.

EEA (2002) The Biogeographical Regions Map of Europe. European Environment Agency, Copenhagen, Denmark.

Elena-Rosselló R (1997) Clasificatión Biogeoclimática de España Peninsular y Balear. Ministerio de Agricultura, Pesca y Alimentación, Madrid, Spain.

ERDAS (1997) ERDAS Field Guide, 4th edn. ERDAS Incorporated, Atlanta, Georgia, USA.

ESRI (2002) ArcGIS 8.2. Environmental Systems Research Incorporated, Redlands, California.

Ewert F, Rounsevell MDA, Reginster I, Metzger MJ, Leemans R (2005). Future scenarios of European agricultural land use. I: Estimating changes in crop productivity. Agriculture Ecosystems and the Environment 107: 101-116.

FAO (1991) The Digitised Soil Map of the World (Release 1.0), Rep. No. 67/1. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO/IIASA (2000) Global Agro-Ecological Zones (Version 1.0). Food and Agriculture Organization of the United Nations, Rome, Italy.

Faust NL (1989) Image Enhancement. Marcel Dekker Inc., New York, USA.

Firbank LG, Barr CJ, Bunce RGH, Furse MT, Haines-Young RH, Hornung M, Howard DC, Sheail J, Sier A, Smart SM (2003) Assessing stock and change in land cover and biodiversity in GB: an introduction to Countryside Survey 2000. Journal of Environmental Management 67: 207-218.

Global Soil Data Task (2000) Global Soil Data Products CD-ROM (IGBP-DIS). International Geosphere-Biosphere Programme, Data and Information System, Potsdam, Germany. Available from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. [http://www.daac.ornl.gov]

Godron M (1994) The natural hierarchy of ecological systems. In: Klijn F (ed) Classification for environmental management Kluwer Academic Publishers, Dordrecht, The Netherlands, pp 69-83.

Haines-Young RH, Barr CJ, Black HIJ, Briggs DJ, Bunce RGH, Clarke RT, Cooper A, Dawson FH, Firbank LG, Fuller RM, Furse MT, Gillespie MK, Hil R, Hornung M, Howard DC, McCann T, Morecroft MD, Petit S, Sier ARJ, Smart SM, Smith GM, Stott AP, Stuart RC, Watkins JW (2000) Accounting for nature: assessing habitats in the UK countryside. DETR, London, UK.

Hill MO, Gauch HG (1980) Detrended correspondence analysis, an improved ordination technique. Vegetaio 42: 47-58.

Hulme M, Conway D, Jones PD, Jiang T, Barrow EM, Turney C (1995) Construction of a 1961-90 European climatology for climate change modelling and impact applications. International Journal of Climatology 15: 1333-1363.

Hutchinson MF, Gessler PE (1999) Splines: more than just a smooth interpolator. Geoderma 62: 45-67.

IMAGE team (2001) The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate change and impacts in the 21st century. National Institute of Public Health and the Environment, Bilthoven, The Netherlands.

Jalas J, Suominen J (eds) (1976) Atlas Flora Europaea, distribution of Vascular Plants in Europe, Vol. 3. The Committee for Mapping the Flora of Europe & Societas Biologica Fennica Vanamo, Helsinki, Finland.

Jensen JR (1996) Introductory Digital Image Processing: A Remote Sensing Perspective. Prentice-Hall, Englewood Cliffs, New Jersey, USA.

Jones HE, Bunce RGH (1985) A preliminary classification of the climate of Europe from temperature and precipitation records. Journal of Environmental Management 20: 17-29.

Jongman RHG, Braak CJF ter, Tongeren OFR van (eds) (1995) Data analysis in community and landscape ecology. Cambridge University Press, Cambridge, UK.

Jongman RHG, Bunce RGH, Metzger MJ, Mücher CA, Howard DC, Mateus VL (2005) Objectives and applications of a statistical environmental stratification of Europe. Landscape Ecology. In press.

Kendrew WG (1953) The climate of the continents, 4th edn. Oxford University Press, London, UK.

Klijn F, Haes HAU de (1994) A hierarchical approach to ecosystems and its implications for ecological land classification. Landscape Ecology 9: 89-104.

Leathwick JR, Overton JM, McLeod M (2003a) An environmental domain classification of New Zealand and its use as a tool for biodiversity management. Conservation Biology 17: 1612-1623.

Leathwick JR, Wilson G, Rutledge D, Wardle P, Morgan F, Johnston K, McLeod M, Kirkpatrick R (2003b) Land Environments of New Zealand. Bateman, Auckland, New Zealand.

Leser H (1976) Landschaftsokologie. Verlag Eugen Ulmer, Stuttgard, Germany.

Leser H (1991) Landschaftsokologie, 3rd edn. Verlag Eugen Ulmer, Stuttgard, Germany.

Lugo AE, Brown SL, Dodson R, Smith TS, Shugart HH (1999) The Holdridge Life Zones of the Conterminous United States in Relation to Ecosystem Mapping. Journal of Biogeography 26: 1025-1038.

Maarel E van der (1976) On the estimation of plant community boundaries. Berichte der Deutschen Botanischen Gesellschaft 89: 15-443.

Mackey BG, Nix HA, Hutchinson MF, McMahon JP, Fleming PM (1988) Assessing representativeness of places for conservation reservation and heritage listing. Environmental Management 12: 501-514,

Metzger MJ, Leemans R, Schröter D, Cramer W, and the ATEAM consortium (2004) The ATEAM vulnerability mapping tool. Quantitative Approaches in Systems Analysis No. 27, CD-ROM publication, Office C.T. de Wit Graduate School for Production Ecology & Resource Conservation (PE&RC), Wageningen, The Netherlands. [Available on the CD-ROM annex to this thesis]

Metzger MJ, Leemans R, Schröter D (2005) A multidisciplinary, multi-scale framework for assessing vulnerabilities to global change. International Journal of Applied Geo-information and Earth Observation. In press. [Chapter 4 of this thesis]

Mitchell TD, Carter TR, Jones PD, Hulme M, New M (2004) A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100). Tyndall Centre Working Paper No. 55. Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK.

Monserud RA, Leemans R (1992). The comparison of global vegetation maps. Ecological Modelling 62: 275-293.

Mücher CA, Champeaux JL, Steinnocher KT, Griguolo S, Wester K, Heunks C, Winiwater W, Kressler FP, Goutorbe JP, Brink B ten, Katwijk VF van, Furberg O, Perdigao V, Nieuwenhuis, GJA (2001) Development of a consistent methodology to derive land cover information on a European scale from Remote Sensing for environmental monitoring: the PELCOM report. Alterra, Wageningen UR, Wageningen, The Netherlands.

New M, Lister D, Hulme M, Maken I (2002) A high-resolution dataset of surface climate over global land areas. Climate Research 21: 1-25.

Noirfalise A (1987) Map of the natural vegetation of the member countries of the European Community and the Council of Europe. Office for Official Publications of the European Communities, Luxembourg, Luxembourg.

Odum HT (1983) Systems Ecology, an introduction. John Wiley & Sons, New York, USA.

Olson DM, Dinerstein E, Wikramanayake ED, Burgess ND, Powell GVN, Underwood EC, d'Amico, JA, Itoua I, Strand HE, Morrison JC, Loucks CJ, Allnutt TF, Ricketts TH, Kura Y, Lamoreux JF, Wettengel WW, Hedao P, Kassem KR (2001) Terrestrial Ecoregions of the Word: A New Map of life on Earth. BioScience 51: 933-938.

Pan Y, Li X, Gong P, He C, Shi P, Pu R (2003) An integrative classification of vegetation in China based on NOAA AVHRR and vegetation - climate indices of the Holdridge life zone. International Journal of Remote Sensing 24: 1009-1027.

Parry ML, Hossell JE, Jones PJ, Rehman T, Tranter RB, Marsh JS, Rosenzweig C, Fischer G, Carson LG, Bunce RGH (1996) Integrating global and regional analyses of the effects of climate change: A case study of land use in England and Wales. Climatic Change 32: 185-198.

Petit S, Firbank R, Wyatt B, Howard D (2001) MIRABEL: Models for integrated review and assessment of biodiversity in European landscapes. Ambio 30: 81-88.

Prentice IC, Cramer W, Harrison SP, Leemans R, Monserud RA, Solomon AM (1992) A global biome model based on plant physiology and dominance, soil properties and climate. Journal of Biogeography 19: 117-134.

Regato P, Castejón M, Tella G, Giménez S, Barrera I, Elena-Rosselló R (1999) Cambios recientes en los paisajes de los sistemas forestales de España. Investigación Agraria. Sistemas y Recursos Forestales 1: 383-398.

Sheail J, Bunce RGH (2003) The development and scientific principles of an environmental classification for strategic ecological survey in Great Britain. Environmental Conservation 30: 147-159.

Smith M, Bunce RGH (2004) Veteran trees in the landscape: a methodology for assessing landscape features with special reference to two ancient landscapes. In: Landscape ecology of trees and forests (ed. Smithers R) IALE,(UK), Colin Cross, Garstang, UK, pp 168-175.

SPSS (2001) SPSS Version 11.0. SPSS, Chicago.

Tappan GG, Sall M, Wood EC, Cushing M (2004) Ecoregions and land cover trends in Senegal. Journal of Arid Environments 59: 427-462.

Tou JT, Conzalez RC (1974) Pattern Recognition Principles. Addison-Wesley Publishing Company, Reading, Massachusetts, USA.

Visser H (2004) The Map Comparison Kit: methods, software and applications. RIVM report 550002005/2004. Bilthoven, The Netherlands.

Walter H (1973) Vegetation of the earth in relation to climate and eco-physiological conditions. Springer Verlag, New York, USA.

Woodward FI, Rochefort L (1991) Sensitivity analysis of vegetation diversity to environmental change. Global Ecology and Biogeography Letters 1: 7-23.

Wrbka T, Szerncsits E, Moser D, Reiter K (1999) Biodiversity patterns in cultivated landscapes: experiences and first results from a nationwide Austrian survey. In: Maudsley MJ, Marshall EJP (eds) Heterogeneity in Landscape Ecology: Pattern and Scale. IALE,(UK), Bristol, UK, pp 3 –17.

Chapter 6

Shifting European environments under climate change

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Submitted to Global Ecology and Biogeography.

Abstract

Aim

To produce a spatial dataset appropriate for the analysis of shifting European environments based on climate change scenarios derived from multiple Global Climate Models. This dataset can be used to assess potential change in ecological resources, both at a European and regional scale, in standard GIS software, making it suitable for a wide range of environmental studies, including biodiversity assessment and regional scenario development.

Location

A 'Greater European Window' with the following boundaries: 11°W, 32°E, 34°N, 72°N.

Methods

The 84 environmental strata of the *Environmental Stratification of Europe* (EnS), determined by statistical clustering of mainly climatic environmental variables, were linked to a state-of-the-art gridded climate change dataset. Fisher's discriminant functions were calculated for each EnS stratum. Using these functions, the future distribution of principal European environments was mapped for four Global Climate Models and four emission scenarios. Principal environmental shifts in Europe were summarized. Insights into shifting environments for four sample regions were combined with ancillary data to hypothesize the potential impacts on agriculture, forestry and biodiversity.

Results

A brief summary of potential environmental shifts in Europe, as well as a dataset of 84 shifting principal European environments is provided, in a standard GIS format. The dataset has a 10 arcmin longitude-latitude resolution, and is available for baseline conditions and three future time slices (2020, 2050, 2080) for four Global Climate Models and four emission scenarios.

Main conclusions

Europe is likely to experience major environmental shifts, confirming current scientific consensus. As analysis of the four sample regions shows, the impacts of such shifts depend greatly on regional characteristics. The dataset presented here forms a useful tool for integrating relevant ancillary data sources in the assessment of potential impacts on biodiversity, land cover, and land use, using standard GIS software.

Introduction

There is a growing consensus among scientists and the general public that the climate is changing, and that climate change could have serious impacts not only on natural ecosystems, but also on human well-being (IPCC, 2001abc ; EEA, 2004 ; Reid *et al.*, 2005). Over the past 100 years, global surface temperature has risen by about 0.7°C, exceeding the natural variation of the past 1000 years (IPCC, 2001a). Evidence of climatic change impacts are also accumulating: reductions in size of glaciers (Arendt *et al.*, 2002 ; Thompson *et al.*, 2002), melting permafrost (Kwong & Gan, 1994 ; Serreze *et al.*, 2000), shifts in tree lines (Chmielewski & Rötzer, 2001 ; Kullman, 2001), and changes in the length of the growing season (Chmielewski *et al.*, 2003). Furthermore, phenological changes and range shifts have been observed in many species groups (Parmesan & Yohe, 2003 ; Root *et al.*, 2003 ; Leemans & Van Vliet, 2004). Recent newspaper articles also report the widely observed declines in rainfall in southern Spain and support much other anecdotal evidence of desertification.

Anticipating future climate change can help governments adapt to the changes and implement relevant policy measures. The Intergovernmental Panel on Climate Change (IPCC) has developed a range of alternative emission scenarios, based on different socio-economic development pathways for the 21st century (Nakicenovic *et al.*, 2000). There is general agreement between the Global Climate Models (GCMs), which were run for the emission scenarios, that global mean global temperature will rise between 1.6 and 5.8°C by the end of the 21st century (IPCC, 2001a). There is however considerable spatial variation in the projected changes. In addition, there is disagreement between the GCMs in relation to regional climatic patterns and projected changes in precipitation (Ruosteenoja *et al.*, 2003). In order to account for this uncertainty, the IPCC recommends the usage of climate data from multiple GCMs in all climate change impact assessments.

Gridded spatial datasets, containing simulated climatic variables (e.g. Leemans & Cramer, 1991 ; Hulme *et al.*, 1995 ; Mitchell *et al.*, 2004), have been used to further assess potential climate change impacts at global or continental scales. Examples are the global impact assessment model IMAGE (IMAGE team, 2001), dynamic global vegetation models such as LPJ (Sitch *et al.*, 2003), and species distribution models (e.g. Huntley *et al.*, 1995 ; Thuiller *et al.*, 2003 ; Thuiller *et al.*, 2005). Because these modelling exercises generally cover large areas, involve many datasets, and have to be performed for multiple scenarios and GCMs, the complexity of the interactions which can be incorporated is necessarily limited. Complex interactions are simplified, or approximated, and regional heterogeneity in pattern and process are ignored. In addition, these models require considerable technical expertise for their application. Nevertheless, analysis with such ecosystem models are very important for translating abstract changes in the climatic variables into specific potential impacts that are more directly interpretable and relevant in both public debate and the policy arena.

This chapter presents an alternative translation of a high-resolution gridded climate change dataset for Europe (Mitchell *et al.*, 2004). Instead of determining climate response surfaces for specific species (Thuiller, 2003), biomes (IMAGE team, 2001), plant functional types (Sitch *et al.*, 2003), or forest growth (Sabaté *et al.*, 2002), climate functions were determined for the 84 strata of the *Environmental Stratification of Europe* (EnS) (Chapters 5 ; Metzger *et al.*, 2005). The EnS was constructed by statistical clustering of mainly climatic environmental variables into relatively homogeneous regions. By fitting climate functions to the strata, a dataset is constructed that illustrates how principal European environments shift under alternative climate change scenarios, in a similar way to earlier work on shifting biomes (Guetter & Kutzbach, 1990 ; Tchebakova *et al.*, 1993 ; Leemans *et al.*, 1996). However, the EnS distinguishes considerably more classes than the biome classifications, which only distinguish about eight classes in Europe. The new dataset is therefore suitable for more detailed assessments at more regional scales, as demonstrated for four sample regions in this chapter.

While the EnS strata are generic compared to modelling exercises conducted for a specific issue (e.g. biodiversity, forestry, carbon sequestration), they form a convenient summary of climatic shifts projected for Europe. As shown in Chapter 5, under current climatic conditions, the EnS strata show significant correlations with potential natural vegetation, soil, land cover and species distribution. While these correlations may change in the future (Prentice *et al.*, 1992), the climate envelopes associated with the EnS strata form useful units for determining potential changes in ecological resources (cf ecological niche modelling ; Huntley *et al.*, 1995 ; Thuiller *et al.*, 2005). Shifting strata have been applied to assess agricultural yield shifts under climate change (Ewert *et al.*, 2005), and vegetation change in a biodiversity assessment (EURURALIS, 2004 ; Verboom *et al.*, 2005). Furthermore, by combining the shifting strata with ancillary data, more complex analyses are possible, as demonstrated in this chapter for four sample regions. In this way, the shifts in distribution of strata can be used to develop regional land use change scenarios, and to assess combined impacts of climate and land-use change on species dispersal, as argued for by Opdam & Wascher (2004).

The dataset of shifting environmental strata is based on the TYN SC1.0 dataset (Mitchell *et al.*, 2004). It consists of GIS files, with a 10 arcmin longitude-latitude resolution, for baseline conditions (1960-1990) and three time slices (1990-2020, 2020-2050, 2050-2080) for four scenarios, and four GCMs. By making this dataset public, European environmental scientists have access to a convenient climate change dataset, based on state-of-the-art scenarios and multiple GCMs, usable in standard GIS software.

Materials and methods

All GIS operations were performed using ArcGIS version 8.2 (ESRI, 2002), statistical operations were performed in SPSS version 11 (SPSS, 2001).

Datasets

Environmental Stratification of Europe

Stratification into relatively homogenous regions is important for both strategic random sampling of ecological resources and consistent modelling across large heterogeneous regions (Jongman *et al.*, 2005). The *Environmental Stratification of Europe* (EnS) was created using tried-and-tested statistical procedures so that the strata are unambiguously determined and, as far as possible, independent of personal bias. Based on experience from previous studies, 20 of the most relevant available environmental variables were selected. These are (1) climatic variables from the Climatic Research Unit (CRU) TS1.2 dataset (Mitchell *et al.*, 2004), (2) elevation data for the United States Geological Survey HYDRO1k digital terrain model, (3) indicators for oceanicity and northing. Principal Components Analysis (PCA) was then used to compress 88% of the variation into three dimensions, which were subsequently clustered using an ISODATA clustering routine. The classification procedure is described in detail in Chapter 5.

The EnS consists of 84 strata, which have been aggregated into 13 Environmental Zones (EnZs). The EnS strata have been given systematic names based on a three letter abbreviation of the EnZ to which the stratum belongs, and an ordered number based on the mean first principal component score of the PCA. For example, the EnS stratum with the highest mean principal component score within the Alpine North EnZ is named ALN1 (Alpine North one). The stratification has a 1 km^2 resolution.

Aggregations of the strata have been compared to other European classifications using the Kappa statistic, and show 'good' comparisons (Chapter 5 ; Fig. CP8). The EnS shows strong statistical correlations with other European environmental datasets (e.g. those for soil, Potential Natural Vegetation, and species distribution, cf Table 5.4 and Fig. 5.4). Finally, the individual strata have been described using data from available environmental databases.

High resolution grids of monthly climate grids

The TYN SC1.0 dataset consists of monthly climate information based on climatological observations and on outputs from transient coupled atmosphere-ocean GCM simulations (Mitchell *et al.*, 2004). The dataset has a spatial resolution of 10 arcmin longitude-latitude (for Europe approximately 16 km x 16 km), and contains mean monthly values for five climate variables from 2001-2100. A similar dataset, but for observed values (referred to as CRU TS1.2), has been constructed for the period 1901-2000 (New *et al.*, 2002). The variables in these datasets are: temperature, diurnal temperature range, precipitation, cloud cover, and vapour pressure. For the present study, four 30-year time slices were calculated for the climate datasets, as averages of the variables. These periods are: 1961-1990, 1991-2020, 2021-2050, and 2051-2080.

In order to provide as full a representation of the uncertainties in projections of regional climate change as possible, climate change scenarios were developed for four alternative greenhouse gas emission scenarios and four GCMs. The emission scenarios are based on the four narratives (A1, A2, B1, B2) of the IPCC special report on emission scenarios (SRES ; Nakicenovic *et al.*, 2000). Each narrative is characterized by consistent driving forces of greenhouse gas emissions, including demographic change, economic development, and technological development. To incorporate the range of potential changes that may occur for a given region it is advised that the results from a number of GCM experiments are used (Viner, 2002). The four GCMs used in this study, discussed in detail by the IPCC (2001a), are: HadCM3, CSIRO2, NCAR PCM, CGCM2. The 16 climate change scenarios, resulting for the combination of the GCMs and the emission scenarios, cover 93% of the range of uncertainty in global warming in the 21st century published by the IPCC. Thus these scenarios permit users to assess the implications for climate impacts of some major source of uncertainty in future climate.

Shifting environments

The original GIS file of the EnS (as discussed in Chapter 5), with a spatial resolution of 1 km^2 and an equal area projection, was resampled to the 10 arcmin grid of TYN SC1.0 dataset (Mitchell *et al.*, 2004), using the nearest neighbour resampling algorithm in the ArcGIS software. Each grid cell of the 10 arcmin longitude-latitude EnS dataset was subsequently coupled to mean monthly values for the 1969-1990 average of four climatic variables from the

TYN SC1.0 dataset. These climate variables were: temperature, diurnal temperature range, precipitation, and cloud cover. Values for latitude and oceanicity, defined as the July-January temperature range divided by the sine of the latitude, were classification variables in the EnS, and therefore also linked to each grid cell. The resulting attribute table consists of 3114 rows (one for each grid cell), 62 climatic attributes and an identifier for the EnS stratum to which each grid cell belongs.

The attribute table was imported in SPSS to calculate Fisher's discriminant functions (Fisher, 1936 ; McLachlan, 1992) for each EnS stratum. Given a set of interrelated variables, discriminant analysis determines linear combinations of those variables that best separate a set of distinct groups or classes. Fisher's linear discrimination rule finds a linear combination of the variables and determines the coefficients so that the ratio of the difference of the means of the linear combinations in the groups to its variance is maximized. Thus, the procedure maximizes the ratio of the between-group sum of squares and the within-group sum of squares and is identical to the one followed by Bunce *et al.* (1996a).

The equality of group means was tested in order to assess whether all 62 predictors could potentially contribute to the discriminant analysis. A one-way ANOVA was therefore performed for each variable, using the grouping variable as the factor. In addition, Wilks' Lambda, a multivariate test statistic, was calculated. Lower values of Wilks' Lambda indicate that the variable is more effective at discriminating between groups.

Fisher's linear discriminant functions were exported from SPSS and used in ArcGIS to determine the future distribution of the 84 strata from variables of TYN SC1.0. Separate maps were created for the three time slices (2020, 2050, 2080) for each emission scenario and four GCMs (i.e. HadCM3, CSIRO2, NCAR PCM, CGCM2). The shift from the baseline environment was determined for the 2080 time slice in order to summarize the projected environmental shift for each grid cell. These shifts were summarized for each EnZ, indicating the direction of the shift, the area which had shifted to a different EnZ, and the relative change in area of the EnZs. Agreement in the shifts across CGMs and scenarios was analysed with Student's t-test.

As validation of the discriminant functions, the EnS strata predicted by the discriminant functions for baseline conditions were compared with the original map. Furthermore, to test whether the shifted EnS strata do indeed represent the climatic change projected by the climate dataset, mean values of the climatic variables were calculated for each EnS stratum under baseline conditions. For the future time slices, these values were use to project climatic change as determined by the shifting EnS strata. Regional summaries, per EnZ, of these projections were compared with regional summaries from the TYN SC1.0 climate dataset by linear regression through the origin, for seasonal averages of the climate variables. In addition, box plots were created, again per EnZ, for the differences between the projected climate variables as expressed by the shifting EnS strata, and the TYN SC1.0 dataset.

Sample regions

For specified regions, insights into potential shifts of environmental strata, combined with ancillary data and knowledge of experts, can be used to explore potential impacts of climate change, as demonstrated for by Bunce *et al.* (1996b) for the Cairngorm environment in Scotland. Four contrasting sample regions were chosen for which shifting environments will be discussed to further illustrate the way in which the current stratification can be used to summarize shifts in European environments. The selected sample regions are: southern Sweden, the southern Carpathian mountains, the north-western part of the Iberian Peninsula, and south-western England and Wales (see Fig. 6.1). The Swedish region is discussed in most detail. The other regions illustrate contrasting impacts projected across Europe.

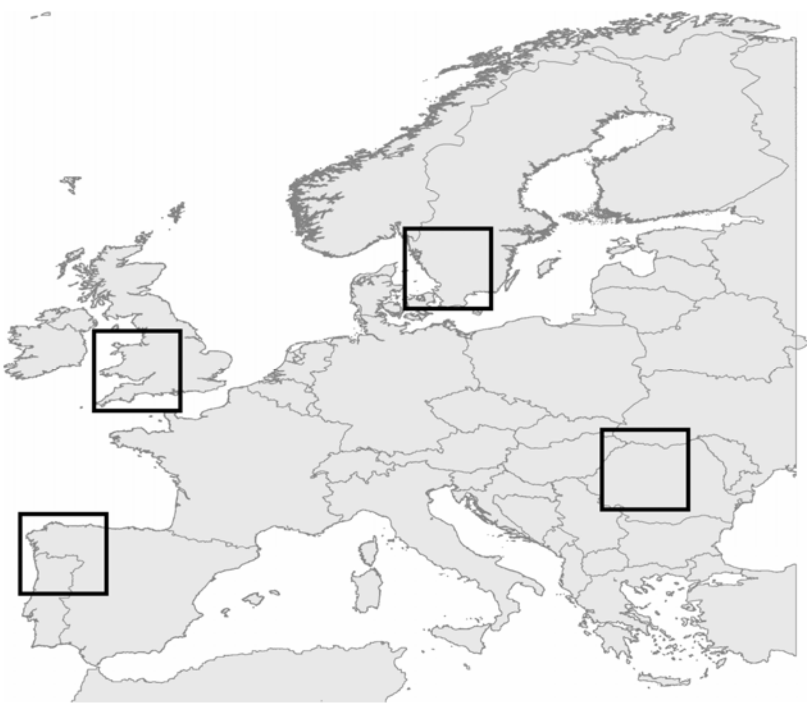

Figure 6.1. Map of Europe showing the location of the four sample regions.

For the sample regions, maps of the EnS strata are presented for baseline conditions and the 2080 time slice, for one emission scenario (A1) and one GCM (HadCM3). In addition, seasonal maps of change in mean maximum temperature (in °C) and mean precipitation (in %) are presented, which assist in the interpretation of the shifting strata. For Sweden, maps are provided for four GCMs, in order to show how variability between GCM projections is translated into the EnS strata. Finally, for each sample region a map, and for Sweden also a table, is presented which help illustrate the environmental characteristics for the baseline EnS strata, and can thus be used to interpret potential impacts. The environmental data presented include: figures on growing season, wheat productivity (Ewert *et al.*, 2005), agricultural land use (Eurostat NewCronos), distribution maps of *Fagus sylvatica* and *Quercus ilex* s.l. (Köble & Seufert, 2001), the Potential Natural Vegetation map of Bohn *et al.* (2000), and the principal land cover types from the PELCOM dataset (Mücher *et al.*, 2001).

In most regions, there is a strong coincidence between land use, climate, geomorphology, soil, and market demand. For the sample regions it will be illustrated how the shifting climatic strata and some basic ancillary information can be used as a first indication of the potential impacts of climate change. More detailed regional assessments can be developed by combining further ancillary datasets on geomorphology and soils, as well as socio-economic scenarios describing alternative changes in demand (cf Rounsevell *et al.*, 2005).

Results

Shifting European environments

The one-way ANOVA, performed to test of the equality of group means for the 62 predictor variables, was significant for all variables. The values for Wilks' Lambda, indicating how well each variable discriminates between the strata, did vary between the variables. The oceanicity indicator had the highest value (0.337), indicating the lowest discriminating power. The temperature variables had the lowest values (ranging between 0.023-0.086). Values for precipitation and sunshine were greater (respectively ranging between 0.140-0.230 and between 0.047-0.174).

For the baseline situation, the discriminant functions classified 75.2% of the grid cells correctly. This percentage varied between EnS strata from 38% to 98%. In seven cases, less that 50% of the grid cells were correctly classified. Misclassified grid cells are assigned to EnS strata which are relatively similar (i.e. have a nearby EnS number, indicating a close distance along the first principal component of the EnS classification variables, as discussed in Chapter 5.

The regression analysis, comparing projected change in climatic variables based on shifted EnS strata with the TYN SC1.0 climate dataset was significant is all cases (four variables, four scenarios, four GCMs). The R^2 of these linear regressions through the origin was in all cases greater than 0.95. Nevertheless, box plots for the difference between the variables projected by the shifting EnS and the climate dataset do show that in most regions temperature change projected by the GCM is about 2°C greater than the prediction by the shifting EnS (Fig. 6.2). For precipitation and sunshine the prediction by the shifting EnS resembles the climate dataset quite well (see Fig. 6.2).

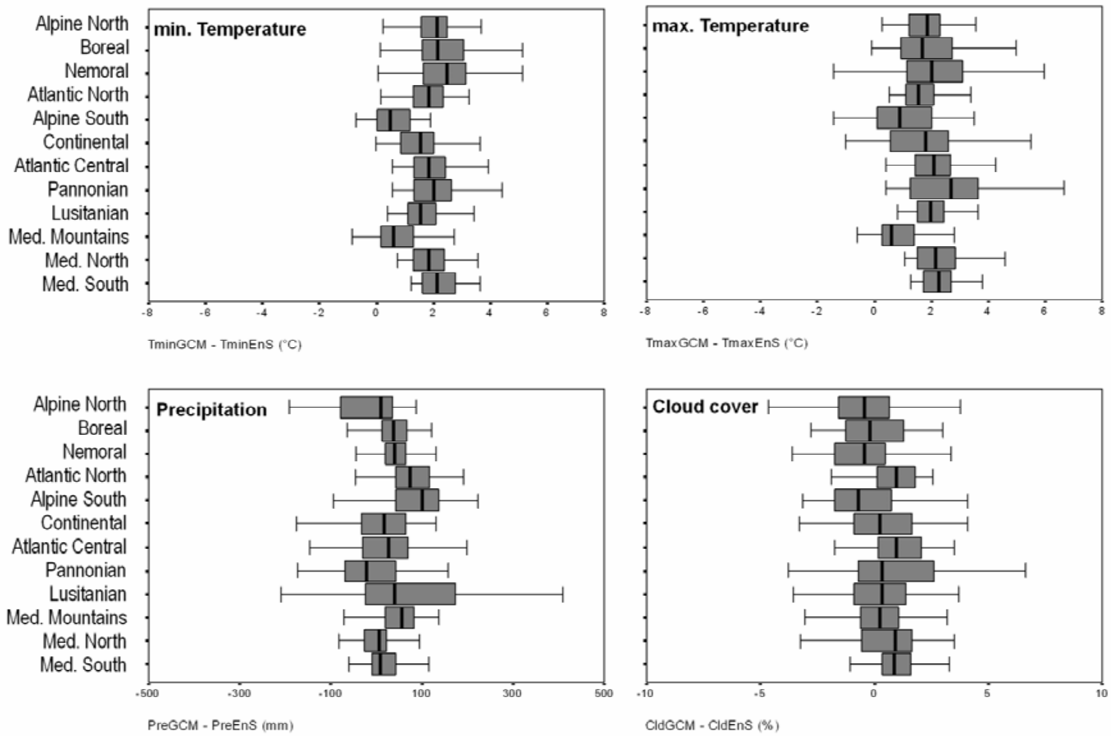

Figure 6.2. Box plots, per Environmental Zone, showing the difference between four climatic variables, as projected by the TYN SC1.0 climate dataset and values associated with the EnS strata. The shifting EnS strata underestimate temperature by about 2°C. For precipitation and cloud cover the shifting EnS strata give a good representation of the climate dataset.

Maps created for time series in the 21st century show how environments expand, contract, shift, or remain stable. Fig. CP12 gives an example of shifting environments, for the three time slices, for one GCM and emissions scenario. For presentation purposes, the maps have been aggregated into the 13 EnZs. However, the detail is provided by the 84 EnS strata, as can be seen in the results for the sample regions.

When the maps for the different GCMs and scenarios are seen as independent observations of the future environment of Europe, all changes in extent are significant, except for Alpine North and Atlantic North (Table 6.1). Fig. CP13 illustrates the projected shifts between EnZs which are positioned in the environmental space, determined by the first two principal components of the PCA used for the EnS (Chapter 5). Arrows indicate the shifts between EnZs. The relative increase or decrease of each EnZ is given in the circle, the size of which refers to the current extent of each zone.

The arrows in Fig. CP13 illustrate that more southern environments shift northwards, confirming the concerns among the majority of climate change scientists. Some more detailed observations are listed below:

- The drier and warmer Mediterranean South zone expands northwards into the Mediterranean North environment.
- Lusitanian environments become drier and shift into Mediterranean North.
- Mediterranean Mountains and Alpine South environments decrease dramatically, and become warmer Mediterranean North and Continental environments, respectively.
- The Continental zone faces complex changes. On the one hand it expands into the Alpine and Carpathian mountain ranges. On the other hand, in the east it shifts into the drier Pannonian, but in the west to the wetter Atlantic Central environments.
- The Atlantic Central zone shifts northwards into Atlantic North, but also expands into the Continental zone.
- For northern Europe, the GCMs make contradictory projections. As a result, changes for Atlantic North and Alpine North are not significant (Table 6.1), and Fig. CP13 has arrows of equal thickness in opposite directions between Atlantic North and Boreal. Nevertheless there is agreement that Nemoral environments shift northward, and Boreal environments decrease in extent.

Table 6.1. Changes in extent of the Environmental Zones in 2080 compared to baseline conditions, summarized across 16 climate change scenarios (four GCMs and four emission scenarios). (a) Absolute change in square kilometres. (b) Relative change.

(a) Absolute change (x1000 km^2)

	mean change	SE	95% ll	95% ul	T test	
Alpine North	18.0	155.7	-58.3	94.3	0.651	
Boreal	-241.7	148.0	-314.2	-169.2	0.000	**
Nemoral	37.3	196.1	-58.8	133.4	0.000	**
Atlantic North	68.1	150.0	-5.4	141.5	0.090	
Alpine South	-132.5	34.4	-149.4	-115.7	0.000	**
Continental	-135.5	172.1	-219.8	-51.2	0.007	**
Atlantic Central	232.1	201.9	133.2	331.1	0.000	**
Pannonian	81.6	115.8	24.9	138.3	0.000	**
Lusitanian	-91.3	65.0	-123.1	-59.4	0.000	**
Mediterranean Mountains	-106.7	58.4	-135.3	-78.1	0.000	**
Mediterranean North	177.3	101.6	127.5	227.1	0.000	**
Mediterranean South	84.0	84.1	42.8	125.2	0.000	**

**Significant at 1% level.

(b) Relative change

	mean change	SE	95% ll	95% ul	T test	
Alpine North	5.6	48.8	-18.3	29.5	0.651	
Boreal	-27.9	17.1	-36.3	-19.5	0.000	**
Nemoral	6.1	32.1	-9.6	21.8	0.000	**
Atlantic North	20.9	46.2	-1.7	43.6	0.090	
Alpine South	-53.3	13.9	-60.1	-46.5	0.000	**
Continental	-11.8	15.0	-19.2	-4.5	0.007	**
Atlantic Central	41.4	36.0	23.7	59.0	0.000	**
Pannonian	20.7	29.4	6.3	35.1	0.000	**
Lusitanian	-42.3	30.1	-57.1	-27.5	0.000	**
Mediterranean Mountains	-30.8	16.9	-39.1	-22.6	0.000	**
Mediterranean North	30.2	17.3	21.7	38.6	0.000	**
Mediterranean South	28.1	28.1	14.3	41.9	0.000	**

**Significant at 1% level.

Sample regions

Southern Sweden

This region is mainly situated within the Nemoral EnZ, which includes Europe's northern limits for agriculture and some deciduous tree species. Approximately 40% of the area is used as arable land, mainly for cereals (barley, oats, and wheat) as well as forage production (Eurostat NewCronos). The remaining area is mostly covered by forest, predominantly coniferous, with some beech (*Fagus sylvatica*) and oak (*Quercus* spp) forests in the south. Birch (*Betula* spp) is present throughout the region. Natural vegetation is determined by human induced agricultural and forest landscapes.

Under the climate change scenarios, the region is projected to become warmer and wetter. There is considerable variation in regional patterns between the four CGMs, especially for precipitation (Fig. CP14). There is however a general northward shift in the EnS strata. Changes in precipitation patterns will result in a strong expansion of Atlantic environments, which varies from a minor northwards shift of ATN5, the most northerly Atlantic stratum (HadCM3), to the arrival of Atlantic Central strata currently found in France (CGCM2). Interestingly, CSIRO2 projects a southward expansion of BOR8. This appears to be caused by a strong increase in spring precipitation, characteristic of BOR8.

As can be deduced from Table 6.2, the projected environmental shifts will have favourable consequences for plant growth, leading to an expanded growing season, higher temperature sums, and higher productivity. As a result, the region would become more suitable for more temperate crops. More importantly, yields of currently grown crops are likely to increase significantly (Ewert *et al.*, 2005). Similar increases in productivity would also occur for tree species, which would be favourable for forestry. Deciduous tree species, e.g. *Fagus sylvatica*, which has its northern limits in stratum NEM6 (Fig. CP14), could also expand northwards. While natural migration is likely to be slow, forest management could influence distribution patterns by creating spaces for regeneration. Climate change is also likely to influence biodiversity, e.g. through the expansion of weed species with southern distributions (e.g. *Picris echioides*). Nevertheless, management effects, both in agriculture and forestry, are likely to be more widespread than effects of climate change.

In this region, there is a strong coincidence between land use and soil. The acidic soils associated with the Scandinavian shield, with most of the forest cover, will limit the potential expansion of agriculture. Furthermore, agricultural expansion does not seem likely when at a European scale agricultural land is being taken out of production due to overproduction, as suggested by alternative land use change scenarios (Rounsevell *et al.*, 2005). The main conclusion for this sample region is therefore that climate change will positively influence agricultural and forestry production, but will not cause major shifts in land use or biodiversity.

Table 6.2. Mean statistics for the ten EnS strata projected to occur in the Swedish sample region. The table shows difference in growing season, grain yield (Ewert *et al.*, 2005), relative proportion cereal crops (Eurostat NewCronos), and the relative area of two types of Potential Natural Vegetation (PNV) (Bohn *et al.*, 2000).

EnS stratum	**growing season**	**grain yield**	**wheat**	**oats**	**PNV deciduous**	**PNV coniferous**
	(days > 10°)	(t ha^{-1})	(% area of cereal area)			
BOR8	177	4.24	19%	31%	0%	93%
NEM3	190	5.28	22%	32%	4%	80%
NEM5	204	6.5	24%	26%	39%	45%
NEM6	201	6.71	26%	28%	3%	71%
CON3	213	6.05	no data	no data	8%	11%
CON10	220	6.5	no data	no data	9%	4%
ATN5	226	7.2	43%	2%	1%	0%
ATC1	327	8.05	26%	6%	9%	0%
ATC4	270	7.23	64%	2%	0%	0%
ATC5	299	6.63	62%	1%	8%	0%

Carpathian mountains

This sample region covers a large part of the Carpathian mountain range in Romania and the Transylvanian plain. The mountain range has peaks of over 2000 m, with Alpine grasslands harbouring endemic species (e.g. *Bruckenthalia spiculifolia*). The slopes of the mountains are covered by spruce forests, and lower on the slopes mixed forests, and deciduous forests. The plain is covered by arable and grassland, the latter containing distinct Pannonian species (e.g. *Ferula sadleriana*). However, these grasslands are largely a result of over-exploitation by man, and the Potential Natural Vegetation for this region is considered to be beech and mixed coniferous broad-leaved forests (Bohn *et al.*, 2000).

Under the climate change scenarios, summers are projected to be much warmer and drier. The other seasons will also be warmer, but winter and spring are projected to be wetter. As Fig. CP15.1 shows, this translates into major environmental shifts. Most notably, the Carpathian environments have disappeared, with the exception of Mt. Moldoveanu (2544 m). They are replaced by EnS stratum CON12 (currently low mountains and undulating plains in south-eastern Europe) and for the higher altitudes CON8 (currently the foothills of the South Carpathians). The plains also change in character: They are now covered by PAN3, the driest, steppic, Pannonian stratum.

The projected environmental shifts are likely to cause major changes in the vegetation of the mountain range, because the species restricted to high elevation will have no comparable environments into which they can disperse. Other effects can be deduced from current land cover and maps of potential vegetation (Fig. CP15.1). Deciduous tree species will be able to expand to higher altitudes as the climate becomes more mesic. Similarly, the spruce forests will regenerate in the Alpine grasslands, causing a loss of endemic species. This process could occur relatively rapidly, because there will be little competition for the colonizing spruce trees in the grasslands. This would be comparable to the reported expansion of forests at high altitudes in Scandinavia (Austad *et al.*, 2004). In the plains, the shifting environment will have less influence on biodiversity. The current Pannonian characteristics, maintained by human influence, are likely to be enhanced by the drier and warmer climate, and more pronounced steppic species are likely to expand at the expense of less extreme species. For arable crops the change will probably have serious consequences, because they are anyway at the edge of their range and will be affected by drier conditions.

North-western Iberian Peninsula

This sample region covers Galicia and the western Cantabrian mountains (Spain), and northern Portugal. Near the Atlantic coast, the region has a moist, Lusitanian climate. Towards the south-east, the region becomes drier and the character changes to Mediterranean, with associated species such as *Quercus ilex* (see Fig. CP15.2). The Lusitanian region is characterized by heathland vegetation, eucalyptus plantations, and a fine-scale mosaic of agricultural land uses including intensive pastures, cereal production, and some vineyards. This fine pattern is related to the variability in geomorphology and soils. The Mediterranean part of the region is covered mainly by arable land, dominated by low yielding cereal production, and grassland.

The climate change scenario projects considerable warming, especially in the summer, which is also projected to be much drier. The winters are projected to be somewhat wetter. However, the moist, Lusitanian character is projected to change into more Mediterranean environments because of the drier summers (Fig. CP15.2). Only small fragments of the Lusitanian strata are likely to remain. Also, as in the Carpathians, the mountain environments of the Cantabrian mountains will almost disappear. Finally, the southern part of the region changes from a comparatively moderate northern Mediterranean environment into very dry southern Mediterranean environments.

The projected environmental shifts are likely to have large impacts on the vegetation in the region. True Mediterranean species, such as *Quercus ilex* s.l. (Fig. CP15.2) will be able to rapidly expand into regions which are currently moist. While any future shifts will be limited by the geomorphology and soil characteristics, dispersal distances from the current species pool in the south are short, and species such as *Cistus monspeliensis* will be strong competitors for the Lusitanian species (e.g. *Erica tetralix*). Eucalyptus plantations are unlikely to be affected by a warmer climate. However, there is likely to be an increased risk of forest fires in the drier parts of the region, and these are also likely to be hotter because of the current build-up of organic matter. Rainfed agriculture will become a considerable challenge.

South-west England and Wales

The region is characterized by an Atlantic climate. In the east, EnS stratum ATC2 has a high proportion of intensive arable land (>65%) consisting mainly of wheat, barley, and forage plants (Eurostat NewCronos). The western part of the region contains uplands, with extensive grasslands, heathlands and small wetlands (ATN3: the Cambrian mountains and southern Pennines) and a few alpine species at higher altitudes in Snowdonia (ATN1). The lower hills of Cornwall and South Wales (ATC3) are dominated by productive pastures, mainly of monocultures of *Lolium perenne*. Fig. CP16 illustrates the strong relationship between the EnS strata and land cover.

The climate change scenario projects a relatively minor temperature rise compared to the three other sample regions because of buffering of the climate by the Atlantic Ocean. There are changes in precipitation patterns, with drier summers and wetter winters. Nevertheless, as shown in Fig. CP16, the EnS strata are relatively stable, with only a slight expansion of the warmer ATC4, and a slight decrease in upland environment.

Although the impacts of the shifting environments are far less pronounced than in the other sample regions, some of the changes are still likely to have impacts. Warmer summers, and increased droughts could negatively affect agriculture. On the other hand, the changes could benefit productivity, especially of the grassland. Some adaptation to the new climate conditions will be required, but other socio-economic changes (e.g. changes in agricultural policy or increased tourism) are likely to be of greater consequence to the agricultural industry than climate change. Wetlands and south-facing slopes, currently areas of high biodiversity, may face declines in more northern species (e.g. *Rubus chamaemorus*) due to higher temperatures. Conversely, species with southern distribution patterns and currently restricted distributions (e.g. *Erica vagans* and *Rubia peregrina*) are likely to expand. The upland vegetation is likely to resist such minor changes, but bogs may dry-out causing loss of species such as *Narthecium ossifragum* which require high water levels. Migration of new species to the area is restricted, because invasive species will have to cover a significant distance across the Channel.

Discussion and conclusions

The aim of the present study was to create a dataset which is appropriate for the analysis of shifting European environments under climate change. *A priori*, the usefulness of the final dataset depends on the definition of European environments and the quality of the climate change dataset. Both datasets were considered the most suitable of their kind at the present time. The *Environmental Stratification of Europe* forms the most detailed quantitative classification of the European environment currently available (Chapter 5 ; Metzger *et al.*, 2005). The TYN SC1.0 climate change dataset (Mitchell *et al.*, 2004) has the highest spatial resolution of the gridded datasets available for Europe at this time. A further advantage of this dataset is the fact that data are available for four socio-economic emission scenarios and four GCMs, giving as full a representation of uncertainties in regional climate change as possible (cf Fig. CP14). Communication of the results from impacts assessments to the policy community is difficult and as yet there appears to be no suitable framework available to incorporate the sources of uncertainty, besides taking into account alternative development pathways and multiple GCMs (Viner, 2002).

Discriminant analysis formed a recognized multivariate approach for assigning climate functions to the 84 EnS strata. While the variation in Wilks' Lambda indicated differences in discrimating power between groups of variables (i.e. temperature most discriminating, followed by sunshine and precipitation), the groups means were significant for all variables, indicating that they could potentially contribute to the function. Therefore, all variables were included in the discriminant analysis. Results show that the discriminant functions are reasonably successful, correctly classifying 75.2% of the grid cells for baseline conditions. Because misclassification will occur especially for strata which are relatively similar in climatic properties, consequences of such misclassification are limited.

One assumption in the current approach of shifting environments is that, while environments can shift, the relative climate profiles of the environments remain unchanged. The box plots in Fig. 6.2 show that this is not the case for temperature. In 2080, EnS strata are about 2°C warmer than under baseline conditions. This is important to keep in mind, especially for regions where environments do not shift, such as the south-west England and Wales sample area (Fig. CP16). While at a European scale potential impacts in such regions will be relatively minor, they do become warmer, which can be of great significance at regional scales. For instance, in Britain butterfly species have recently migrated northwards (Hill *et al.*, 1999) and larger numbers of migrating butterflies, including species considered as pests, are expected (Sparks *et al.*, 2005).

The analyses presented refer to environmental shifts, while they are based on climate change scenarios only. As such, they could be misinterpreted. While at a European scale environment is largely determined by climate (Chapter 5), other important elements are ignored. Some of these elements have a strong relation with climate (e.g. potential vegetation, plant productivity), and may also be maintained under projected shifts, but for other elements this will not hold true (e.g. for soil and land use). As suggested before, it is therefore important to combine insights in climatic shifts with ancillary information when assessing potential impacts for a specific region or issue. For instance, in the Swedish sample region (Fig. CP14), it is important to take into account regional soil conditions, land use dynamics, as well as competition and vegetation succession for colonizing deciduous species. When taking these aspects into account, it becomes evident that deciduous tree species are not likely to expand very rapidly, as at first glance might be deduced from the shifting EnS strata.

The shifting EnS strata provide a convenient summary of the climate change scenarios. Monthly values for multiple parameters are summarized in classes with similar climatic profiles. While the summarizing figure of environmental shifts (Fig. CP13) provides a condensed summary of projected shifts between Environmental Zones, the 84 shifting EnS strata can be used as a simple statistical model to determine potential changes in ecological resources. Ewert *et al.*, (2005) have shown how the EnS strata can be combined with agricultural statistics to make simple estimates of yield changes resulting from climate change. Similarly, the shifting strata have been used to determine changes in potential vegetation structure (Verboom *et al.*, 2005). As demonstrated for the sample regions, the dataset can also be used to assess species distribution, especially for species at the edge of their range and where pools of more southern species are available for expansion. In this respect islands such as Great Britain could be more protected from rapid invasion of new species. While such models are less sophisticated than those constructed for one specific aim, they do provide strong signals of projected climatic shifts, including variability between climate change projections from multiple GCMs. When such variability is large, i.e. there is considerable uncertainty in how the climate system will change, effort into more complex modelling may not give results with greater accuracy.

Perhaps the most useful application of the shifting EnS strata, is the possibility to combine insights into climate change with ancillary datasets and expert knowledge, thus linking landscape and biogeographical scale level, as demonstrated for the sample regions (Figs. 6.5-6.8). In the examples, the ancillary data was limited to a few European datasets. When available, detailed regional datasets (e.g. for soil, species distribution, and land use), field observations and local knowledge can be used to make more detailed assessments. Standard GIS operations can then be used to make regional scenarios, useful for evaluating regional or national physical planning and nature conservation. Such analyses can be extended to modelling meta-population behaviour and habitat change, as argued for by Opdam & Wascher (2004). Also, outputs from European impact models can be evaluated at a regional scale. For instance, European biodiversity models can be combined with regional land use scenarios to assess distribution changes in more detail. Such regional studies could be of interest to regional or national governments or NGOs. Alternatively, by selecting representative sites across Europe, impacts on European habitats could be evaluated. Or, by linking sample regions to socio-economic scenarios describing alternative changes in demand (cf Rounsevell *et al.*, 2005), consistent detailed global change scenarios could be developed for selected regions across Europe.

The results reported here show that the dataset of shifting environmental strata is appropriate for summarizing state-of-the-art knowledge about climate change in Europe. As such, it can be applied in simple modelling exercises, or in combination with ancillary data, to hypothesize potential change in ecological resources.

References

Arendt AA, Echelmeyer KA, Harrison WD, Lingle CS, Valentine VB (2002) Rapid wastage of Alaska glaciers and their contribution to rising sea level. Science 297: 382-386.

Austad I, Norderhaug A, Hauge L, Moen A (2004) An overview of Norwegian summer farming. In: Bunce RGH, Pérez-Soba M, Jongman RHG, Goméz Sal A, Herzog F, Austad I eds.Transhumance and biodiversity in European mountains. IALE publication series nr 1, Alterra Wageningen UR, Wageningen, The Netherlands.

Bohn U, Gollub G, Hettwer C (2000) Karte der natürlichen Vegetation Europas: Maßstab 1:2.500.000. Bundesamt für Naturschutz, Bon-Bad Godesberg, Germany.

Bunce RGH, Watkins JW, Brignall P, Orr J (1996a) A comparison of the environmental variability within the European Union. In: Jongman RHG (ed) Ecological and landscape consequences of land use change in Europe. European Centre for Nature Conservation, Tilburg, The Netherlands, pp 82-90.

Bunce RGH, Watkins JW, Gillespie MK (1996b) The Cairngorm environment in a European context and the potential for change. Botanical Journal of Scotland 48: 127-135.

Chmielewski F-M, Rötzer T (2001) Response of tree phenology to climate change across Europe. Agricultural and Forest Meteorology 108: 101–112.

Chmielewski F-M, Muller A, Bruns E, (2004). Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961-2000. Agricultural and Forest Meteorology 121: 69-78.

EEA (2004) Impacts of Europe's changing climate. An indicator-based assessment. EEA report No 2/2004. European Environment Agency, Copenhagen, Denmark.

ESRI (2002) ArcGIS 8.2. Environmental Systems Research Incorporated, Redlands, California, USA.

EURURALIS (2004) A scenario study on Europe's Rural Areas to support policy discussion. WUR/RIVM CDrom publication. Wageningen, Bilthoven, The Netherlands.

Ewert F, Rounsevell MDA, Reginster I, Metzger MJ, Leemans R (2005) Future scenarios of European agricultural land use. I: Estimating changes in crop productivity. Agriculture Ecosystems and Environment 107: 101-116.

Fisher RA (1936) The use of multiple measurements in taxonomic problems. Annals of Eugenics 8: 376-386.

Guetter PJ, Kutzbach JE (1990) A modified Köppen classification applied to model simulations of glacial and interglacial climates. Climatic Change 16: 193-215.

Hill JK, Thomas CD, Huntley B (1999) Climate and habitat availability determine 20th century changes in butterfly's range margin. Proceedings of the Royal Society of London B 266: 1197-1206.

Hulme M, Conway D, Jones PD, Jiang T, Barrow EM, Turney C (1995) Construction of a 1961-90 European climatology for climate change modelling and impact applications. International Journal of Climatology 15: 1333-1363.

Huntley B, Berry PM, Cramer W, McDonald AP (1995) Modelling present and future ranges of some European higher plants using climate response surfaces. Journal of Biogeography 22: 967-1001.

IMAGE team (2001) The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate change and impacts in the 21st century. National Institute of Public Health and the Environment (RIVM), Bilthoven, The Netherlands.

IPCC (2001a) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

IPCC (2001b) Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

IPCC (2001c) Climate Change 2001: Mitigation. Contribution of Working Group III to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

Jongman RHG, Bunce RGH, Metzger MJ, Mücher CA, Howard DC, Mateus VL (2005) Objectives and applications of a statistical environmental stratification of Europe. Landscape Ecology. In press.

Köble R, Seufert G (2001) Novel maps for forest tree species in Europe. Proceedings of the 8th European Symposium on the Physico-Chemical Behaviour of Air Pollutants: 'A Changing Atmosphere!', Torino (It) 17-20 September 2001.

Kullman L (2001) 20tth century climate warming and tree-line rise in the southern Scandes of Sweden. AMBIO 30: 72-80.

Kwong TTJ, Gan TY (1994) Northward migration of permafrost along the Mackenzie highway and climatic warming. Climatic Change 26: 399-419.

Leemans R, Cramer W (1991) The IIASA database for mean monthly values of temperature, precipitation and cloudiness on a global terrestrial grid. International Institute of Applied Systems Analyses (IIASA), Laxenburg, Austria.

Leemans R, Cramer WP, Minnen JG van (1996) Prediction of global biome distribution using bioclimatic equilibrium models. In: Melillo JM, Breymeyer A (eds) Effects of Global Change on Coniferous Forests and Grasslands. John Wiley & Sons, New York, USA.

Leemans R, Vliet A van (2004) Extreme weather: Does nature keep up? Observed responses of species and ecosystems to changes in climate and extreme weather events: many more reasons for concern. Report Wageningen University and WWF Climate Change Campaign, Wageningen, The Netherlands.

McLachlan GJ (1992) Discriminant analysis and statistical pattern recognition. John Wiley & Sons, New York, USA.

Metzger MJ, Bunce RGH, Jongman RHG, Mücher CA, Watkins JW (2005) A climatic stratification of the European environment. Global Ecology and Biogeography. In press. [Chapter 5 of this thesis]

Mitchell TD, Carter TR, Jones PD, Hulme M, New M (2004) A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100). Tyndall Centre Working Paper No. 55. Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK.

Mücher CA, Champeaux JL, Steinnocher KT, Griguolo S, Wester K, Heunks C, Winiwater W, Kressler FP, Goutorbe JP, Brink B ten, Katwijk VF van, Furberg O, Perdigao V, Nieuwenhuis, GJA (2001) Development of a consistent methodology to derive land cover information on a European scale from Remote Sensing for environmental monitoring: the PELCOM report. Alterra, Wageningen UR, Wageningen, The Netherlands.

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, la Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooyen S, Victor N, Dadi Z (2000) IPCC Special Report on Emission Scenarios (SRES). Cambridge University Press, Cambridge, UK.

New M, Lister D, Hulme M, Maken I (2002) A high-resolution dataset of surface climate over global land areas. Climate Research 21: 1-25.

Opdam P, Wascher D (2004) Climate change meets habitats fragmentation: linking landscape and biogeographical scaele levels in research and conservation. Biological Conservation 117: 285-297.

Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421: 37-42.

Prentice IC, Cramer W, Harrison SP, Leemans R, Monserud RA, Solomon AM (1992) A global biome model based on plant physiology and dominance, soil properties and climate. Journal of Biogeography 19: 117-134.

Reid WV, Mooney HA, Cropper A, Capistrano D, Carpenter SR, Chopra K, Dasgupta P, Dietz T, Duraiappah AK, Hassan R, Kasperson R, Leemans R, May RM, McMichael AJ, Pingali P, Samper C, Scholes R, Watson RT, Zakri AH, Shidong Z, Ash NJ, Bennett E, Kumar P, Lee MJ, Raudsepp-Hearne C, Simons H, Thonell J, Zurek MB (2005) Millennium Ecosystem Assessment Synthesis report. Island Press, Washington DC, USA.

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421: 57-60.

Rounsevell MDA, Ewert F, Reginster I, Leemans R, Carter TR (2005) Future scenarios of European agricultural land use II. Projecting changes in cropland and grassland. Agriculture Ecosystems and Environment 107: 117-135.

Ruosteenoja K, Carter TR, Jylhä K, Tuomenvirta H (2003) Future climate in world regions: an intercomparison of model-based projections for the new IPCC emission scenarios. The Finnish Environment 644. Finnish Environment Institute, Helsinki, Finland.

Sabaté S, Gracia CA, Sánchez A (2002) Likely effects of climate change on growth of *Quercus ilex*, *Pinus halepensis*, *Pinus pinaster*, *Pinus sylvestris* and *Fagus sylvatica* forests in the Mediterranean region. Forest Ecology & Management 162: 23-37.

Serreze MC, Walsh JE, Chapin FS, Osterkamp T, Dyurgerov M, Romanovsky V, Oechel WC, Morison J, Zhang T, Barry RG (2000) Observational evidence of recent change in northern high-latitude environment. Climatic Change 46: 159-207.

Sitch S, Smith B, Prentice IC, Arneth A, Bondeau A, Cramer W, Kaplan JO, Levis S, Lucht W, Sykes MT, Thonicke K, Venevsky S (2003) Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Vegetation Model. Global Change Biology 9: 161-185.

Sparks TH, Roy DB, Dennis RLH (2005) The influence of temperature on migration of Lepidoptera into Britain. Global Change Biology 11: 507-514.

SPSS (2001) SPSS Version 11.0. SPSS, Chicago.

Tchebakova NM, Monserud RA, Leemans R, Golovanov S (1993) A global vegetation model based on the climatological approach of Budyko. Journal of Biogeography 20: 219-244.

Thompson LG, Mosley Thompson E, Davis ME, Henderson KA, Brechner HH, Zagorodnov VS, Mashiotta TA, Lin PN, Mikhalenko VN, Hardy DR, Beer J (2002) Kilimanjaro ice core records: Evidence of Holocene climate change in tropical Africa. Science 298: 589-593.

Thuiller W (2003) BIOMOD – optimizing predictions of species distributions and projecting potential future shifts under global change. Global Change Biology 9: 1353-1362.

Thuiller W, Lavorel S, Araújo MB, Sykes MT, Prentice IC (2005) Climate change threats to plant diversity in Europe. Proceedings National Academy of Sciences USA 102: 8245-8250.

Verboom J, Alkemade JRM, Klijn J, Metzger MJ, Reijnen R (2005) EURURALIS: Biodiversity modelling for land-use change scenrios for EU25 countries. Ecological Economics. In press.

Viner D (2002) A Qualitative Assessment of the Sources of Uncertainty in Climate Change Impacts Assessment Studies: A short discussion paper. Advances in Global Change Research 10: 139-151.

Chapter 7

General discussion and conclusions

The vulnerability framework

Comparing across regions and between sectors

The primary aim of this thesis is to present and apply a methodology for mapping vulnerability to global change impacts within the ATEAM project. Chapters 2 and 3 illustrated how the vulnerability framework can be used to make comparisons between ecosystem service indicators, between alternative global change scenarios, and between different regions. By using the *Environmental Stratification of Europe* (EnS) (Chapters 5 and 6; Metzger *et al.*, 2005) it is possible to create a standardized potential impact index for the different ecosystem service indicators. Furthermore, the stratification transformed the indicators within a regional environmental context. The statistically derived EnS strata, thus facilitate comparisons across different environments. In combination with the adaptive capacity index it is possible to create maps of vulnerability that meet the objectives listed in Chapter 1.

The *ATEAM Vulnerability Mapping Tool* (Metzger *et al.*, 2004 ; available on the CD-ROM annex) was developed to allow stakeholders to explore and analyse the vulnerability maps. Furthermore, the maps are presented in fact sheets which contain additional information about uncertainties, assumptions and important conclusions about the ecosystem service indicators. The software contains all the maps created in the ATEAM project, thus allowing users to trace the various steps of the vulnerability framework, including the climate and land use scenarios, the modelled ecosystem service indicators, and the adaptive capacity index. The mapping tool was well received by the ATEAM stakeholders, but it is too early to tell the true effectiveness of the software.

The vulnerability framework was develop for the ATEAM project, but could equally well be applied to other modelled projection of potential impacts, as illustrated in Chapter 4. Furthermore, by linking different stratifications systems, it is possible to compare impacts modelled for different scale level, as demonstrated in the comparison of the ATEAM indicators with output from the global model IMAGE (IMAGE team, 2000).

The vulnerability framework had to be developed and applied within set outlines of the ATEAM project. Nevertheless the principal objectives were met and the methodology has been able to provide important additional insights, as discussed below. Nevertheless, the vulnerability framework is based on a range of assumptions, and has its limitations, as discussed in Chapters 2, 3, and 4. The three greatest limitations in the usefulness of the framework, which apply to most global change assessment, are discussed below.

Limitations

Uncertainty

There are uncertainties attached to any long-term exploration of the future. This is especially true for global change impacts, which are caused by complex global interactions between market forces, demographic development and biophysical processes. The vulnerability framework presented in this thesis forms an extra extension to modelled projections of ecosystem service provision under future scenarios of global change. It is therefore inevitable that within the vulnerability framework complexity and uncertainty is increased. The additional assumptions within the vulnerability framework have been made explicit in Chapters 2, 3, and 4. It is important to realize that while the main motivation for the development of vulnerability framework was the demand for methods to integrate multidisciplinary assessments, such integration comes at the price of additional uncertainty.

Simple adaptive capacity indicator

The ability of communities, regions or sectors to implement adaptation measures will differ across Europe. For the vulnerability framework it was therefore necessary to develop some measure of adaptive capacity that would quantify these differences. Since the publication of the *IPCC Third Assessment Report*, considerable research effort has been aimed at understanding the factors that influence adaptive capacity (Adger *et al.*, 2004 ; Brooks *et al.*, 2005, Pelling & High, 2005 ; Grothmann & Patt, 2005). However, this research is mainly descriptive, and no suitable quantitative indicators of adaptive capacity were available to be used within the vulnerability framework. The current model of adaptive capacity, summarized in most detail in Chapter 3, was developed specifically for the ATEAM vulnerability framework by Klein *et al.* (to be submitted to *Global Environmental Change Part A: Human and Policy Dimensions*). While it provides the possibility to include adaptive capacity in the vulnerability framework, the adaptive capacity index can only be seen as a very generic and coarse indicator. A single indicator is used for all sectors, across the whole of Europe. Furthermore, it does not take into account that local disturbances (e.g. floods, droughts, fires) will have a major influence on *awareness*, one of the three components of adaptive capacity in the current framework. A region affected severely by global change impacts, is more likely to put effort in to increasing future adaptive capacity.

Difficult to relate to regional experience

Although the legend of the vulnerability maps is intuitive, it remains difficult to relate these maps to regional experience, which is of greatest interest to many stakeholders. In the *ATEAM vulnerability mapping tool* (Metzger *et al.*,

2004) it is possible to trace the steps in the vulnerability framework to see how ecosystem service provision and adaptive capacity changes. Nevertheless, it remains difficult to interpret how this will influence regional stakeholders. First of all, this is related to the abstract concepts of vulnerability and adaptive capacity. Furthermore, the uncertainties in the assessment give difficulties in interpretation, especially for smaller regions. Finally, the top-down approach of modelling global change impacts and adaptive capacity for all of Europe ignores regional heterogeneity in land use systems and social structures and limits the interactions that can be modelled. The combination of these three points make that the results from the top-down vulnerability framework will only be useful for a narrow selection of stakeholders, interested in multidisciplinary questions at the EU level.

Future improvements and recommendations

Reduction in uncertainty will increase the usefulness of the vulnerability framework. For example, when more reliable climate change scenarios become available, or when the ecosystem models are able to provide more complex and relevant indicators. Also, it may be possible to improve the adaptive capacity index, for instance by specifying it for different sectors and actors. Nevertheless, it is unlikely that the limitations listed above can be greatly reduced because much of the uncertainty is inherent in the complexity of the human-environment system.

For specified regions, wider insights into global change processes, for instance from assessments such as ATEAM, can be integrated with more detailed ancillary data, knowledge from experts and even new data specifically collected for the assessment, as discussed in Chapter 6. Surveys and other participatory approaches can also be employed to better analyse adaptive capacity. By using more detailed information and narrowing the system, statements about vulnerability can be made with greater confidence, as suggested by Patt *et al.* (2005), but must still be set in the wider context.

There are several ways to choose the sample regions. Sample regions can be targeted at specific regions of interest. Alternatively, by randomly selecting the regions by stratified sampling, using the *Environmental Stratification of Europe* as the framework for stratification, it would be possible to relate findings in the sample to the wider statistical population, as discussed in Chapter 5. In this way it would also be possible to integrate insights from the sample regions with wider modelling approaches, such as the ecosystem models of the ATEAM project.

The vulnerability assessment

Conclusions

Results for Chapters 2 and 3 show that large impacts are projected for ecosystem services provision in Europe. The extent of these impacts differs across regions as well as between ecosystem services. For some ecosystem services negative impacts are projected for one region, while positive impacts are projected for another region (e.g. for *net carbon storage*). The vulnerability framework allows for consistent analysis of this variation, supported by the *ATEAM vulnerability mapping tool* (Metzger *et al.*, 2004). Insight in this variation will be important for different types of European policy, because specific measures may be desired for those regions or sectors that are projected to be most vulnerable.

On the whole, the Mediterranean region is projected to be the most vulnerable to global change. Large environmental shifts are projected (Chapter 6), and the agriculture and nature conservation sectors face negative impacts (Chapters 2 and 3). Forestry may be able to expand slightly, but faces negative impacts from droughts and forest fires. The only positive development for this region is a slight increase in *net carbon storage*. While adaptive capacity is indicated to increase, it is unlikely that the negative impacts can be alleviated fully by adaptation measures.

In the Atlantic region climate change impacts will be relatively minor because of buffering of the climate by the ocean (Chapter 6). Land use change will affect this region, and especially the agricultural sector will face negative impacts (Chapters 2 and 3). Nevertheless, this region, which includes wealthy countries such as Denmark, United Kingdom and France, is indicated to have a high adaptive capacity. Vulnerability of the region will therefore be relatively low.

The vulnerability assessment shows how the alternative development pathways associated with the SRES storylines influence ecosystem service provision. The scenarios associated with strong economic developments and open markets (A-family) generally show the most negative impacts. There are however exceptions, for instance under the A1 scenario agricultural production is concentrated in the most optimal environments, and therefore for Denmark and The Netherlands A1 is the most favourable scenario. Interestingly, the A-family of economic scenarios is also associated with the most rapid development of the adaptive capacity indicator, thus reducing vulnerability.

Relevance

The results from the vulnerability assessment confirm existing knowledge about projected global change impacts in Europe (e.g. Parry, 2000). While stratification of the ecosystem service provision facilitates comparisons between regions, the major differences between southern and north-western Europe have been previously acknowledged. The multitude of maps that have been produced provide the possibility for detailed analyses, but the relevance of such detailed analyses may be limited because of the large uncertainties.

Especially stakeholders interested in a specific sector, or region have indicated that the uncertainties in the projections, combined with difficulties in relating results to their regional situation, limits the usefulness of the assessment in policy development. Furthermore, stakeholders feel that they are better able to estimate their adaptive capacity based on their own experience, than on a generic indicator (Patt *et al.*, 2005).

Nevertheless, the results provided by this assessment could be useful to stakeholders who are interested in multidisciplinary global change issues at the European level, e.g. EU policymakers and representatives from international NGOs. They can use the maps of ecosystem service provision, potential impacts and vulnerability as a spatially explicit portfolio of alternative futures. The provision of ecosystem services can be seen in their interactions, sometimes competing with each other, sometimes erasing or enforcing each other. While such a portfolio is not suitable for direct policy development, it can form a suitable basis for discussion on future policy directions, thereby facilitating sustainable management of Europe's natural resources.

Environmental stratification

During the development of the vulnerability framework it became clear that some form of environmental stratification would be needed in order to make fair comparisons between potential impacts across the European environment. This resulted in the construction of the *Environmental Stratification of Europe* (Chapter 5) and the dataset of shifting European environments (Chapter 6).

The Environment Stratification was developed so that it would be suitable for wider use than the ATEAM vulnerability assessment. One important application is to provide a framework for selecting stratified random samples to assess and monitor habitats and biodiversity. Valid statistical inference requires samples to be representative for the population as a whole. Stratified random sampling is a tried-and-tested procedure for obtaining a representative sample across a heterogeneous environment. For Europe, stratified random sampling provides the possibility to strategically assess and monitor ecological resources, providing robust statistical estimates of extent or change and associated error terms (Smith & Bunce, 2004 ; Jongman *et al.*, 2005). As suggested above, stratified random sample regions could also be used for more detailed vulnerability assessment. A further application of the EnS has been the use of the aggregated Environmental Zones for summary reporting of global change impacts, as shown in this thesis, in the *ATEAM vulnerability mapping tool* and by Thuiller *et al.* (2005).

The dataset of shifting EnS strata forms a convenient summary of projected climate change. Within the ATEAM land use scenarios is was used as a simple model for projecting changes in yield caused by climatic change (Ewert *et al.*, 2005). For specific sample regions, the shifting strata form a useful tool for integrating relevant ancillary data sources in the assessment of potential impacts on biodiversity, agriculture and forestry (Chapter 6). It could therefore also be a useful dataset for place-based, or regional, vulnerability assessments in Europe.

Final conclusions

1. Global change will have a large influence on ecosystem service provision in Europe.

2. There is large heterogeneity in projected vulnerability between regions and ecosystem services.

3. The Mediterranean region is projected to be the most vulnerable, with greatest impacts and lowest indicated adaptive capacity.

4. Wealthy north-western European countries face the lowest impacts and are indicated to have the greatest adaptive capacity.

5. On the whole, the agriculture and nature conservation sectors are projected to be most vulnerable.

6. The presented vulnerability framework is useful for stimulating discussion, and illustrating how vulnerability is influenced by future development pathways.

References

Adger WN, Brooks N, Bentham G, Agnew M, Eriksen S (2004) New Indicators of Vulnerability and Adaptive Capacity. Technical Report 7, Tyndall Centre for Climate Change Research, Norwich, UK.

Brooks N, Adger WN, Kelly PM (2005) The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. Global Environmental Change, 15: 151–163.

Ewert F, Rounsevell MDA, Reginster I, Metzger MJ, Leemans R (2005) Future scenarios of European agricultural land use. I: Estimating changes in crop productivity. Agriculture Ecosystems and Environment 107: 101-116.

Grothmann T, Patt A (2005) Adaptive capacity and human cognition: the process of individual adaptation to climate change. Global Environmental Change. In press.

IMAGE team (2001) The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate change and impacts in the 21st century. National Institute of Public Health and the Environment, Bilthoven, The Netherlands.

Jongman RHG, Bunce RGH, Metzger MJ, Mücher CA, Howard DC, Mateus VL (2005) Objectives and applications of a statistical environmental stratification of Europe. Landscape Ecology. In press.

Metzger, M.J., Leemans, R., Schröter, D., Cramer, W., and the ATEAM consortium (2004) The ATEAM vulnerability mapping tool. Quantitative Approaches in Systems Analysis No. 27, CD-ROM publication, Office C.T. de Wit Graduate School for Production Ecology & Resource Conservation (PE&RC), Wageningen, The Netherlands. [Available on the CD-ROM annex to this thesis]

Metzger MJ, Bunce RGH, Jongman RHG, Mücher CA, Watkins JW (2005) A climatic stratification of the European environment. Global Ecology and Biogeography. In press. [Chapter 5 of this thesis]

Parry M (ed) (2000) Assessment of Potential Effects and Adaptations fro Climate Change in Europe: The Europe ACACIA Project. Jackson Environment Institute, University of East Anglia, Norwich, UK.

Patt A, Klein RJT, Vega-Leinert AC de la (2005) Taking the uncertainty in climate-change vulnerability assessment seriously. C.R. Geoscience 337: 411-424.

Pelling M, High C (2005) Understanding adaptation: what can social capital offer assessments of adaptive capacity? Global Environmental Change. In press.

Smith M, Bunce RGH (2004) Veteran trees in the landscape: a methodology for assessing landscape features with special reference to two ancient landscapes. In: Landscape ecology of trees and forests (ed. Smithers R) IALE,(UK), Colin Cross, Garstang, UK, pp 168-175.

Thuiller W, Lavorel S, Araújo MB, Sykes MT, Prentice IC (2005) Climate change threats to plant diversity in Europe. Proceedings National Academy of Sciences USA 102: 8245-8250.

List of abbreviations

A1 / A2	see SRES
AC	Adaptive capacity
ATEAM	Advanced Terrestrial Ecosystem Analysis and Modelling. The project for which the vulnerability framework was constructed.
B1 / B2	see SRES
CGCM2	GCM used to estimate climate change resulting from greenhouse gas emissions. From Canadian Centre for Climate.
CSIRO2	GCM used to estimate climate change resulting from greenhouse gas emissions. From CSIRO, Australia.
EnS	*Environmental Stratification of Europe*
EnZ	Environmental Zone
ES	Ecosystem service provision
ESstr	Stratified ecosystem service provision
EU	European Union
GCM	Global Climate Model. Model of the climate system that is used to calculate climatic trends from emission scenarios. (Also sometimes called General Circulation Model)
GIS	Geographical Information System
HadCM3	CGM used to estimate climate change resulting from greenhouse gas emissions. From the Hadley Centre, UK.
IMAGE	Integrated Model to Assess the Global Environment.
IPCC	Intergovernmental Panel on Climate Change
NUTS2	Nomenclature des Units Territoriales Statistiques 2: regions or provinces within a country. There are around 500 NUTS2 units, as apposed to only 17 EU countries.
MA	Millennium Ecosystem Assessment
PCM	GCM used to estimate climate change resulting from greenhouse gas emissions. From NCAR, USA.
PI	Potential impact of global change
PIstr	Stratified potential impact to global change
SRES	*Special Report on Emission Scenarios*. There are four scenario families (A1, A2, B1, B2) representing different future worlds with different greenhouse gas emission trajectories.
TAR	*Third Assessment Report* of the IPCC

Colour plates

For many figures in this thesis colour is essential. All colour figures are placed together in a series of 16 colour plates (CP1-16). In the main text, figure references with the letters 'CP' refer to the colour plates. For example: Fig. CP1.2 refers to Fig. 2 on colour plate 1.

Colour plate 1

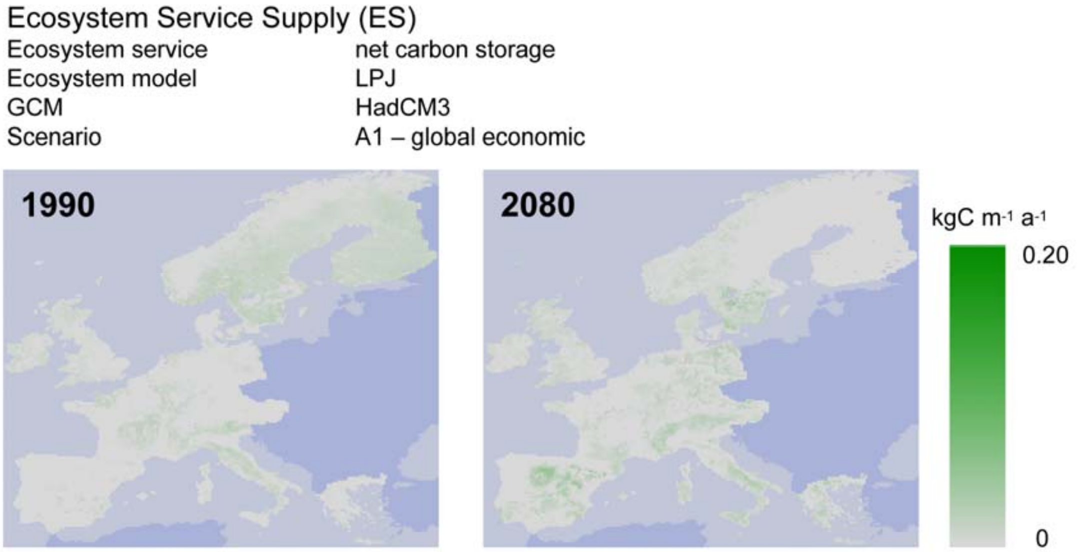

Figure CP1.1. ***Net carbon storage*** across Europe as modelled by the LPJ model for the A2 scenario and the HadCM3 GCM for climate and land use change. Grey areas are net sources of carbon. Carbon emission is not mapped here because in the vulnerability framework ecosystem services and antagonist disservices cannot be mapped together.

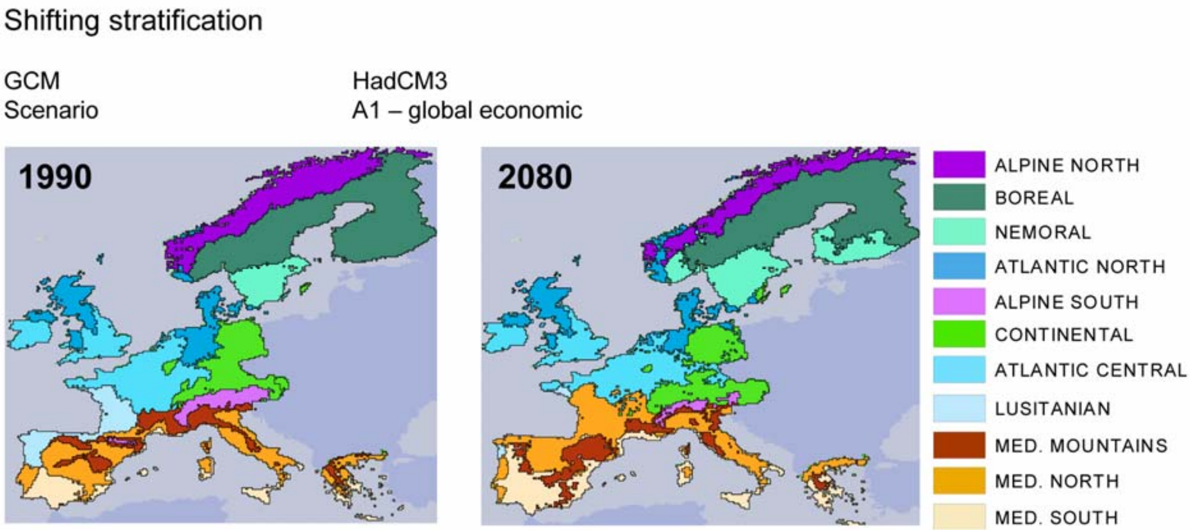

Figure CP1.2. Climatic and topographic variables were statistically clustered into 84 environmental strata. By calculating discriminant functions for the strata they can be mapped for each global change scenario, resulting in maps of shifting climate strata that can be used for stratification. For presentation purposes, here the strata are aggregated to Environmental Zones.

Colour plate 2

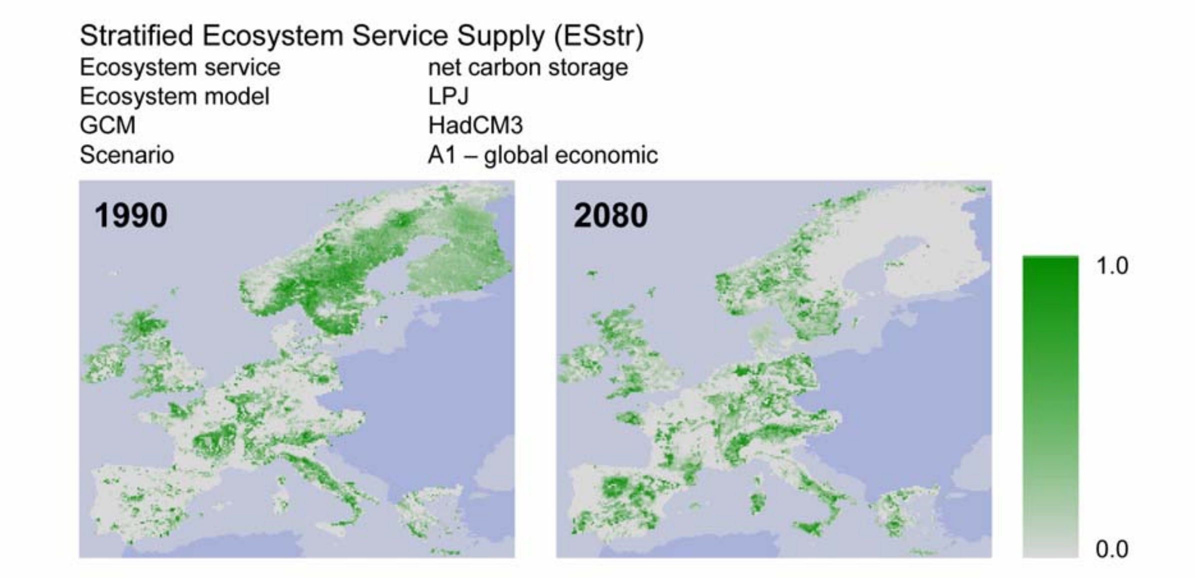

Figure CP2.1. The modelled *net carbon storage* maps are stratified by the environmental strata. Stratified ecosystem service provision maps show greater regional contrast than original, un-stratified maps because ecosystem service provision is placed in a regional instead of a continental context.

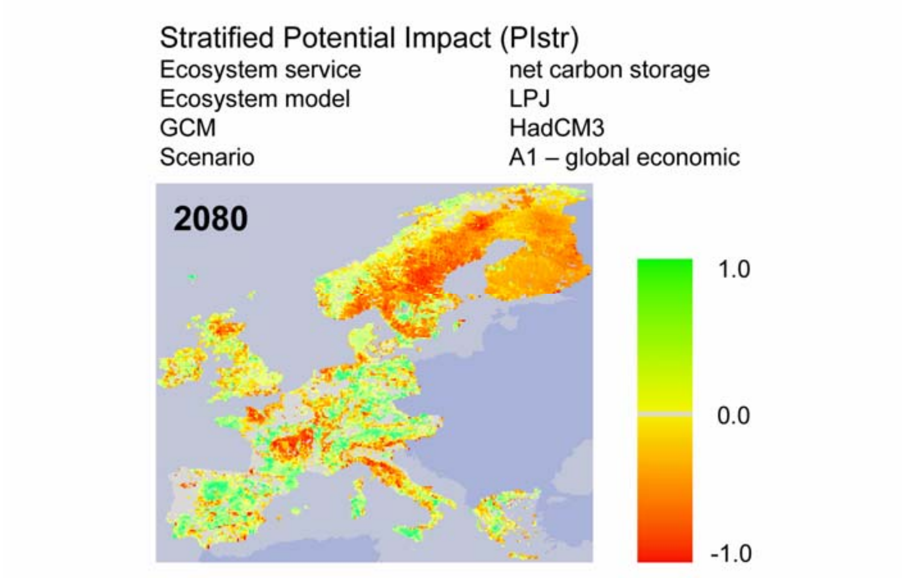

Figure CP2.2. The change in stratified ecosystem service provision compared to baseline conditions forms a stratified measure of the potential impact for a given location. Positive values indicate an increase in ecosystem service provision relative to environmental conditions, and therefore a positive impact, while negative impacts are the result of a decrease in ecosystem service provision compared to 1990.

Colour plate 3

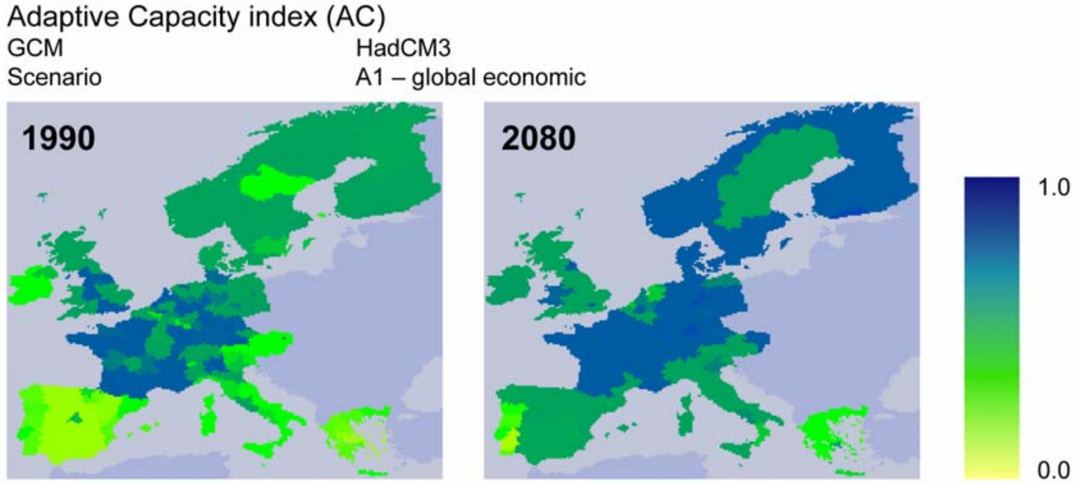

Figure CP3.1. Socio-economic indicators for awareness, ability and action at the regional NUTS2 (provincial) level were aggregated to a generic adaptive capacity index. Trends in the original indicators were linked to the SRES storylines in order to map adaptive capacity in the 21st century. For all regions adaptive capacity increases, but some regions, e.g. Portugal, remain less adaptive than others.

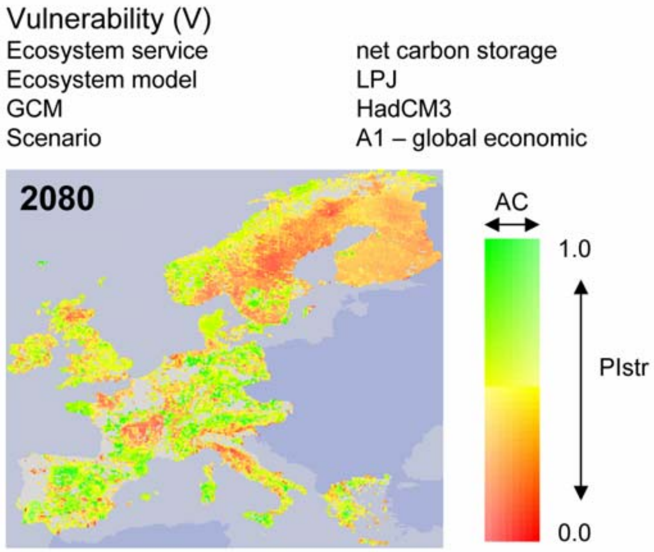

Figure CP3.2. Vulnerability maps combine information about stratified potential impact (PIstr) and adaptive capacity (AC), as illustrated by the legend. An increase in stratified ecosystem service provision decreases vulnerability and *visa versa*. At the same time vulnerability is lowered by human adaptive capacity.

Colour plate 4

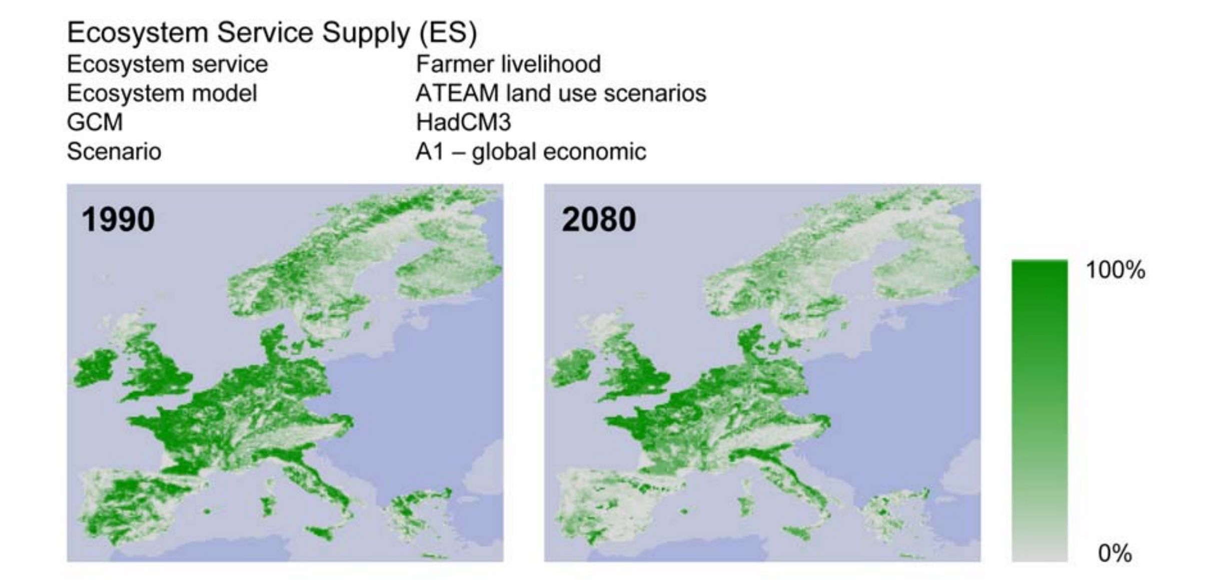

Figure CP 4.1. Ecosystem service supply indicator for *farmer livelihood*, as modelled by the ATEAM land use scenarios for baseline conditions and the A1 scenario for the 2080 time slice.

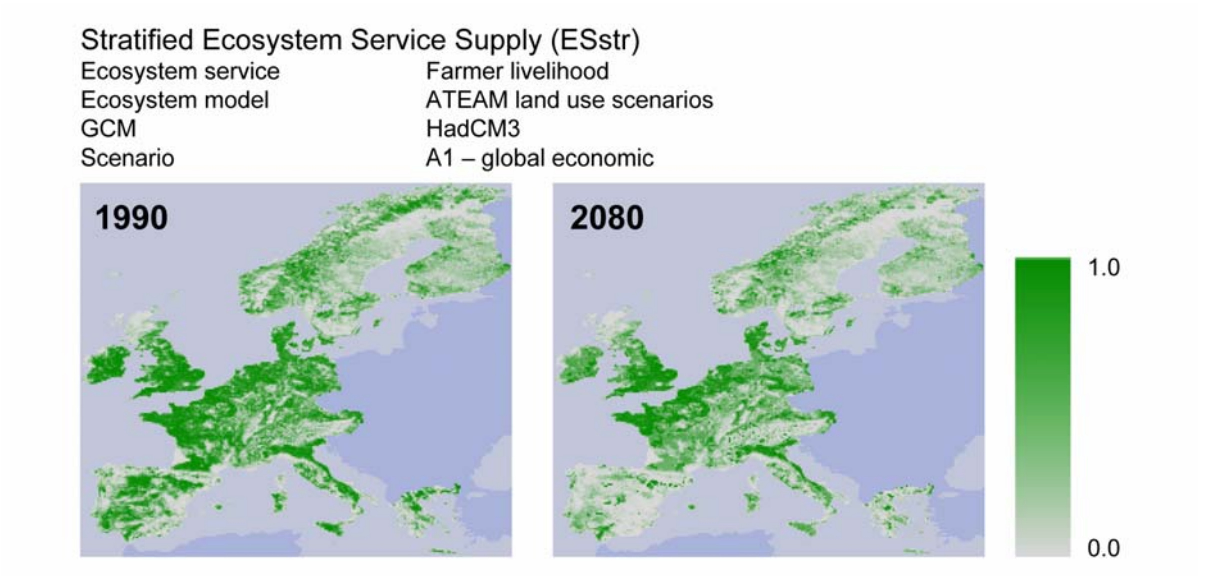

Figure CP4.2. Stratified ecosystem service supply for the ecosystem service indicator *farmer livelihood*. The ecosystem service supply maps for *farmer livelihood* (Fig. CP4.1) are stratified by the environmental strata (Fig. CP1.2).

Colour plate 5

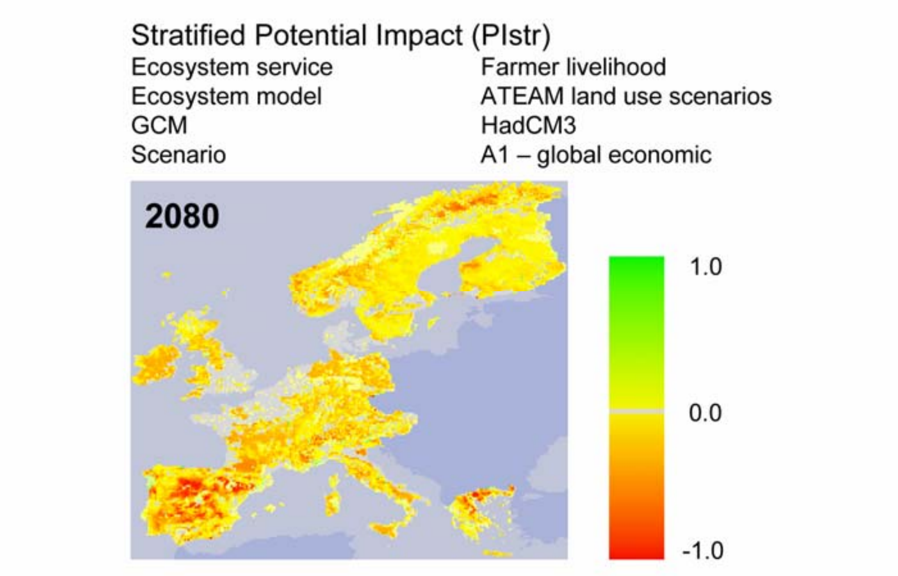

Figure CP5.1. Stratified potential impact for the ecosystem service indicator *farmer livelihood*. Positive values indicate an increase of ecosystem service provision relative to environmental conditions, and therefore a positive potential impact, while negative potential impacts are the result of a relative decrease in ecosystem service provision compared to 1990.

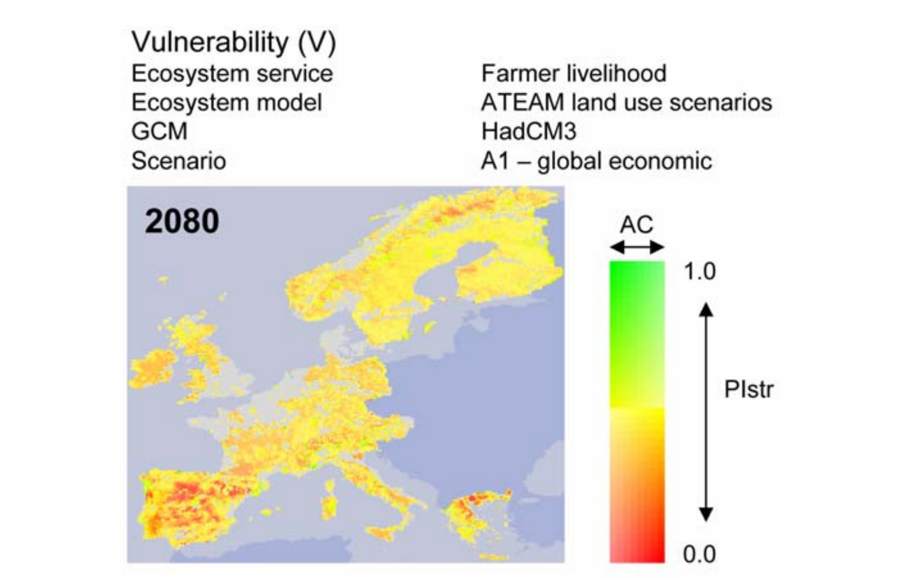

Figure CP5.2. Vulnerability maps for the ecosystem service indicator *farmer livelihood*. These maps combine information about stratified potential impact (Fig. 3.5) and adaptive capacity (Fig. 3.6), as illustrated by the legend. An increase of potential impact decreases vulnerability and visa versa. At the same time vulnerability is lowered by human adaptive capacity.

Colour plate 6

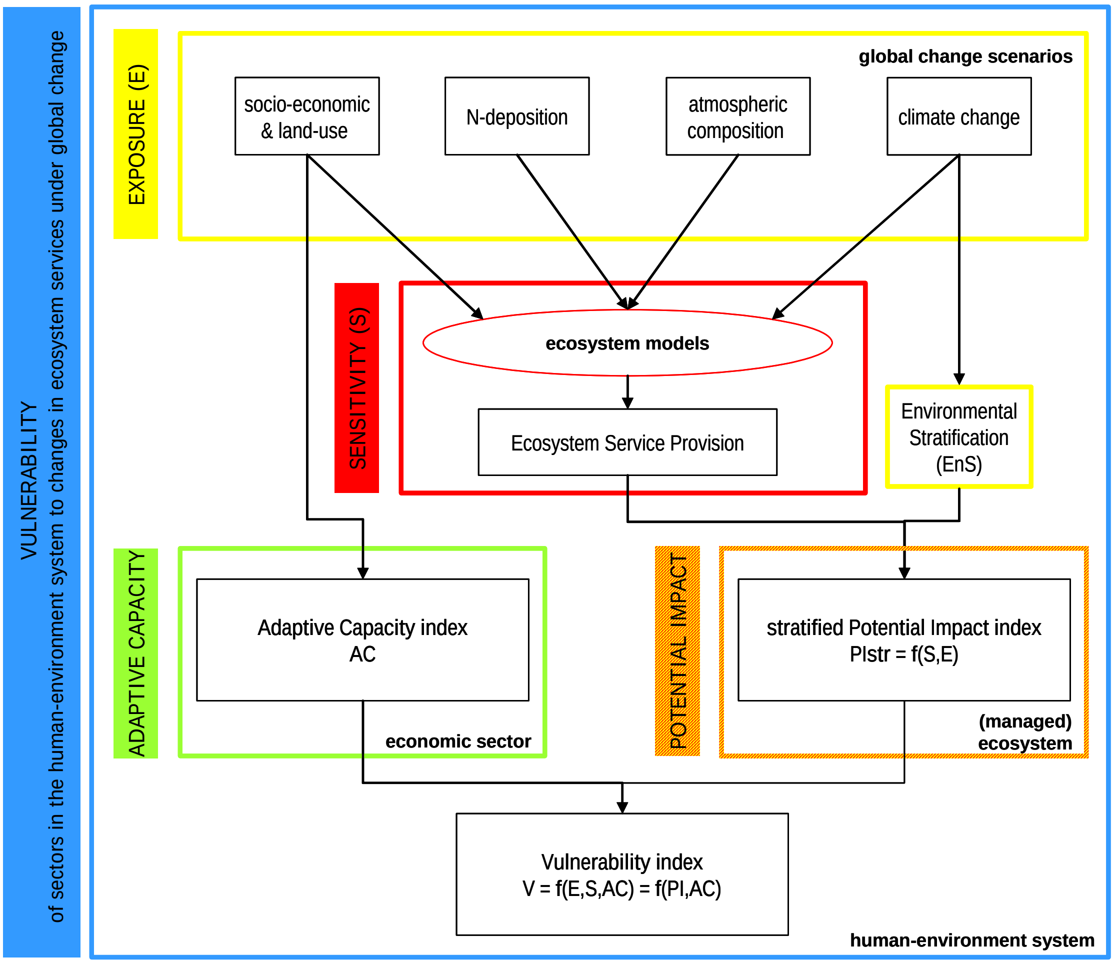

Figure CP6. Summary of the ATEAM approach to quantify vulnerability. Global change storylines and scenarios were used to produce the land use change scenarios. These were linked to several ecosystem service indicators, and provide maps of ecosystem services provision for a 10 arcmin x 10arcmin spatial grid of Europe. The social-economic scenarios are used to project developments in macro-scale adaptive capacity. The climate change scenarios are used to create a scheme for stratifying ecosystem service provision to a regional environmental context. Changes in the stratified ecosystem service provision compared to baseline conditions reflect the potential impact of a given location. The stratified potential impact and adaptive capacity indices can be combined, at least visually, to create European maps of regional vulnerability to changes in ecosystem service provision.

Colour plate 7

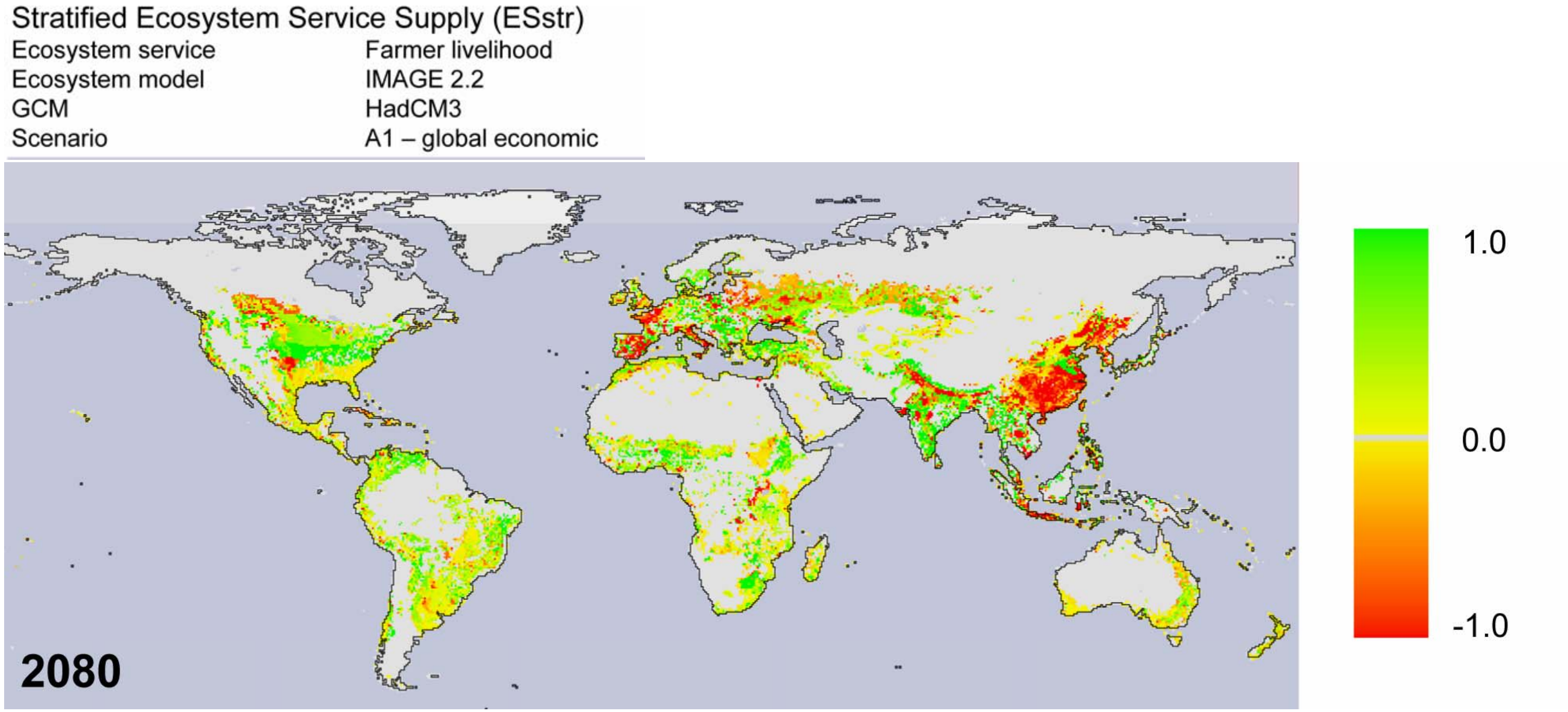

Figure CP7. Stratified potential impact for the ecosystem service indicator *total crop production* for the SRES A1 scenario. Positive values indicate an increase of ecosystem service provision relative to environmental conditions, and therefore a positive potential impact, while negative potential impacts are the result of a relative decrease in ecosystem service provision compared to 1990.

Colour plate 8

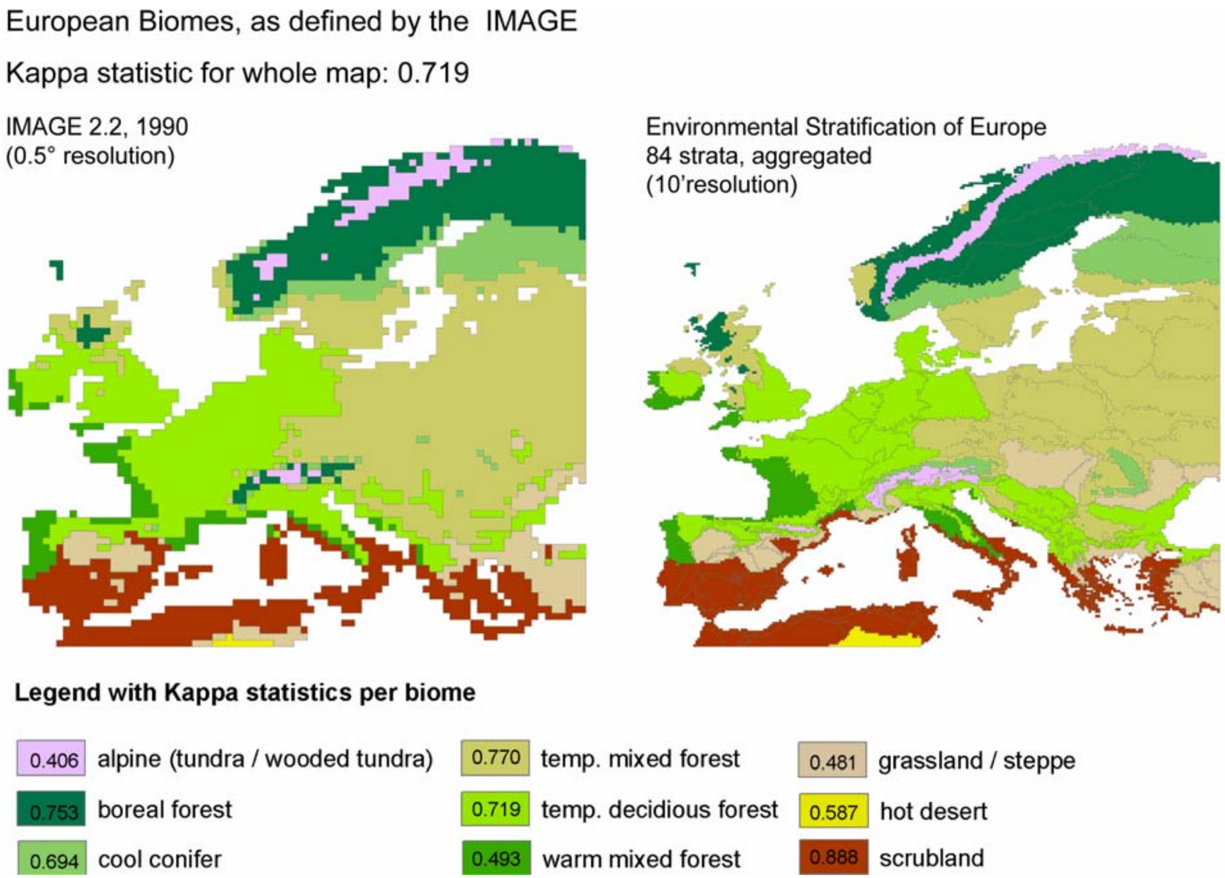

Figure CP8. The 84 strata of the *Environmental Stratification of Europe* (EnS) can be aggregated to resemble the IMAGE biomes. The Kappa statistic, 0.719 for the whole map, indicates a 'very good' agreement between both maps.

Colour plate 9

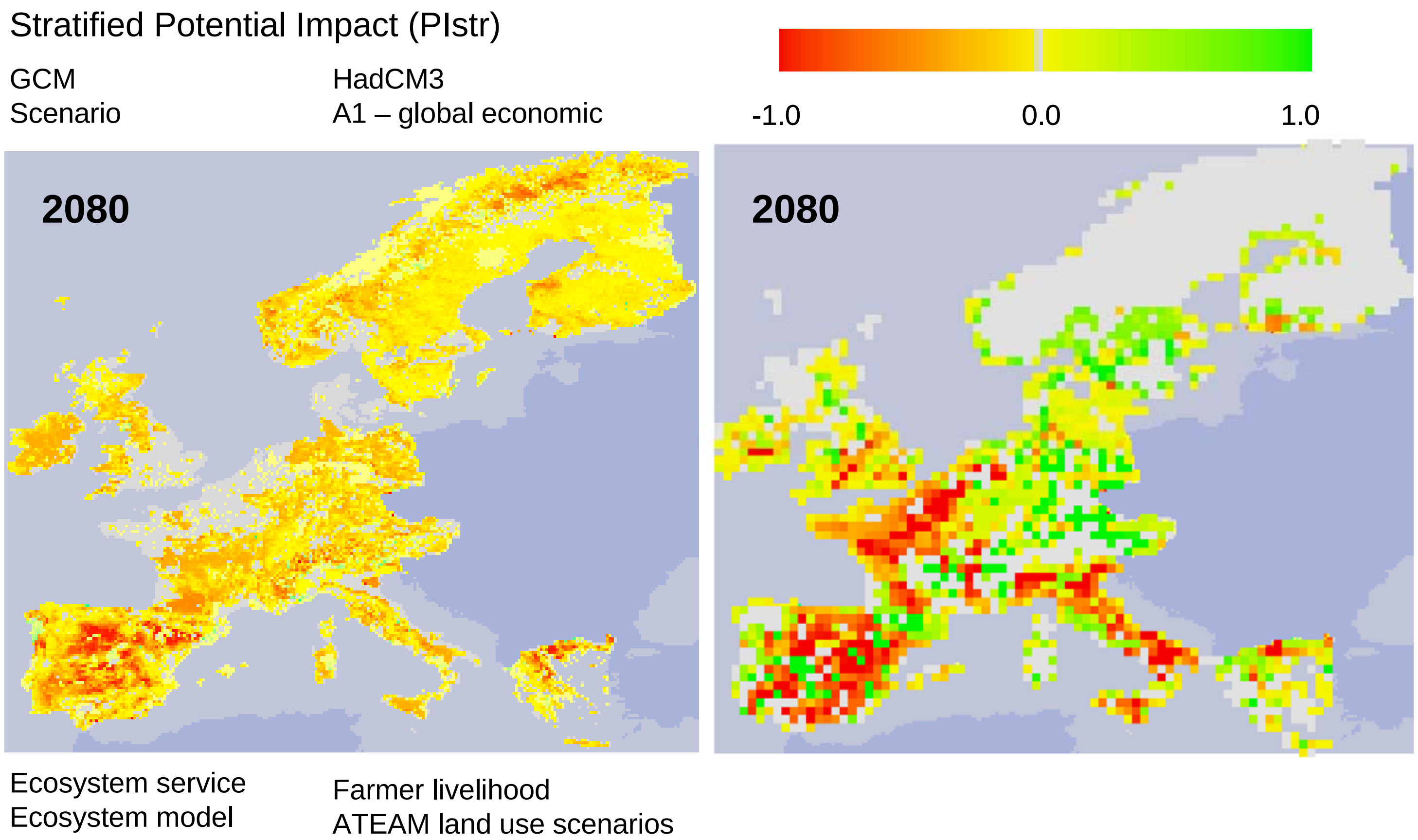

Figure CP9. Maps of changing potential impacts for the ecosystem services ***farmer livelihood*** (10 arcmin resolution) and ***crop production*** (0.5° resolution). Because both maps were created using the same stratification, they can be compared.

Colour plate 10

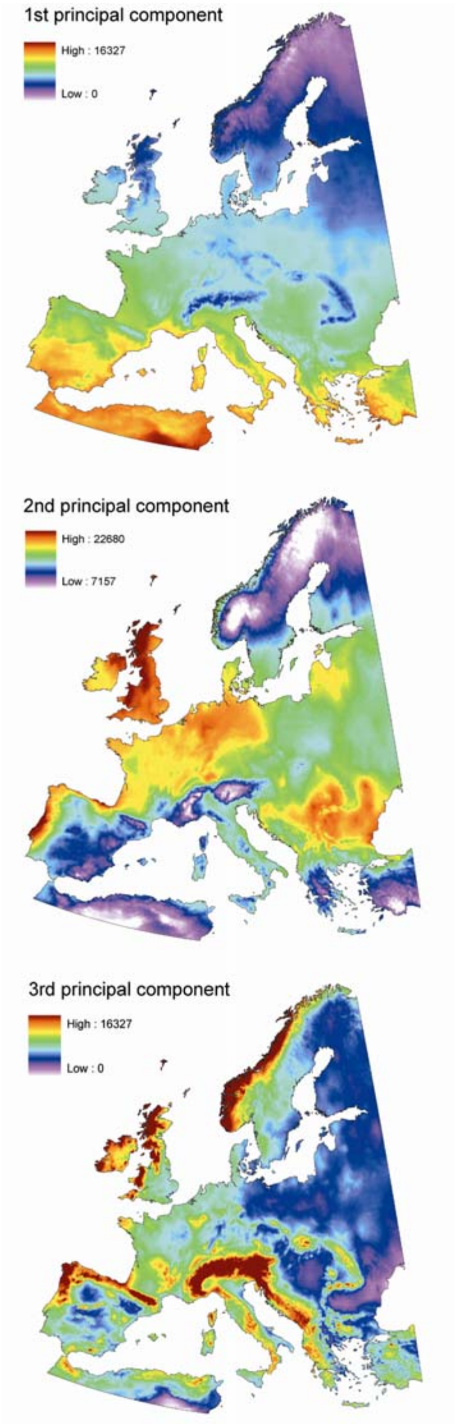

Figure CP10. Maps of the first three principal components of the stratification variables, together explaining 88% of the total variation in the variables. The first principal component, explaining 65% of the variation, expresses the temperature gradient across Europe. The second component, an oceanicity gradient, and the third component, a precipitation pattern, express 15% and 8% of the variation.

Colour plate 11

The Environmental Stratification of Europe

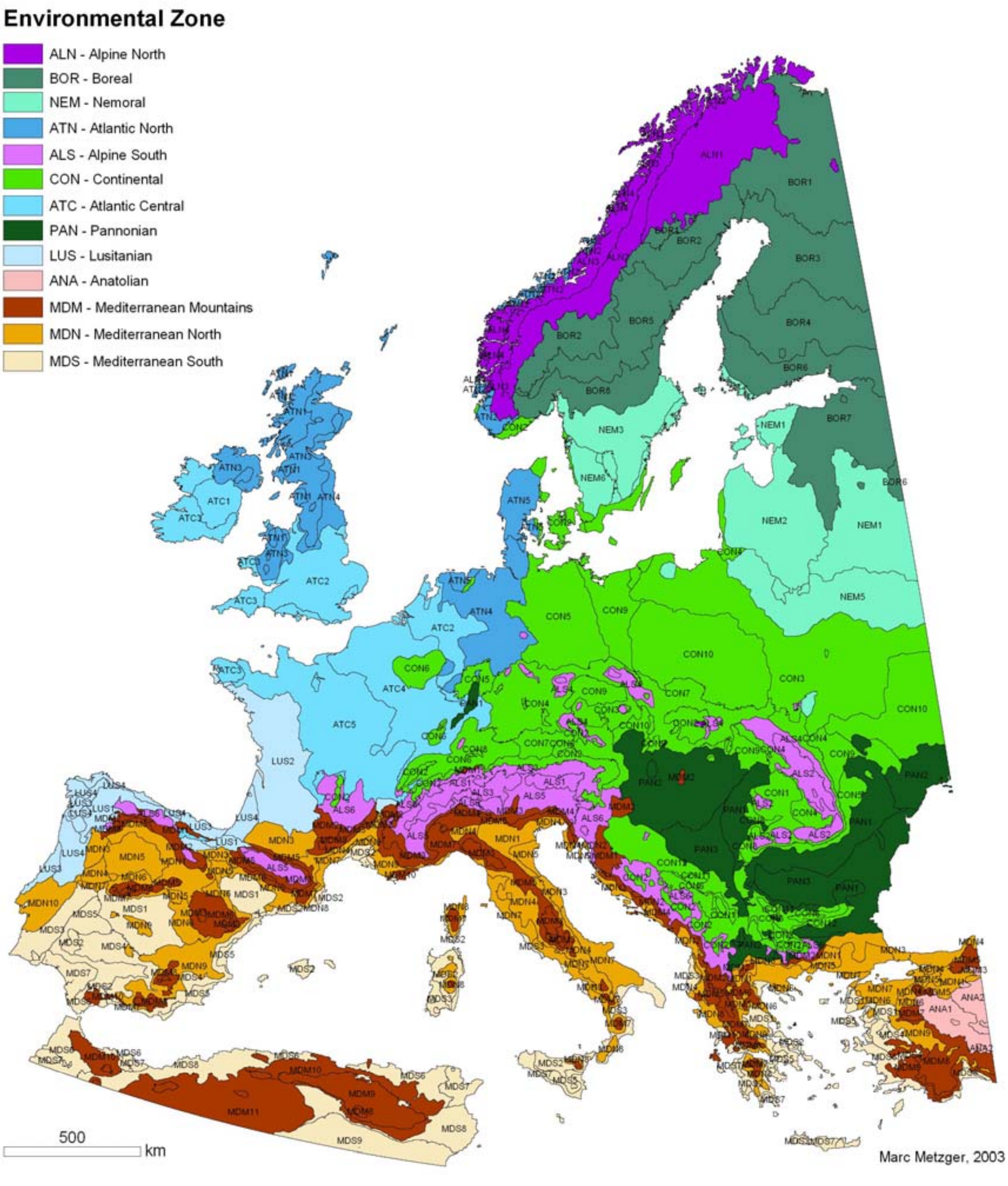

Figure CP11. The *Environmental Stratification of Europe* in 84 strata. Where the size of the stratum permits, the individual strata are labelled within the main Environmental Zones. The stratification extends from 11° West to 32° East and from 34° North to 72° North. It is projected in a Lambert Azimuthal equal area projection. Because certain strata do not necessarily fit traditional experience, in this stratification strict statistical rules have been maintained, recognizing these apparent inconsistencies, e.g. PAN1 in the Vosges and Schwartzwald and CON2 in southern Norway.

Colour plate 12

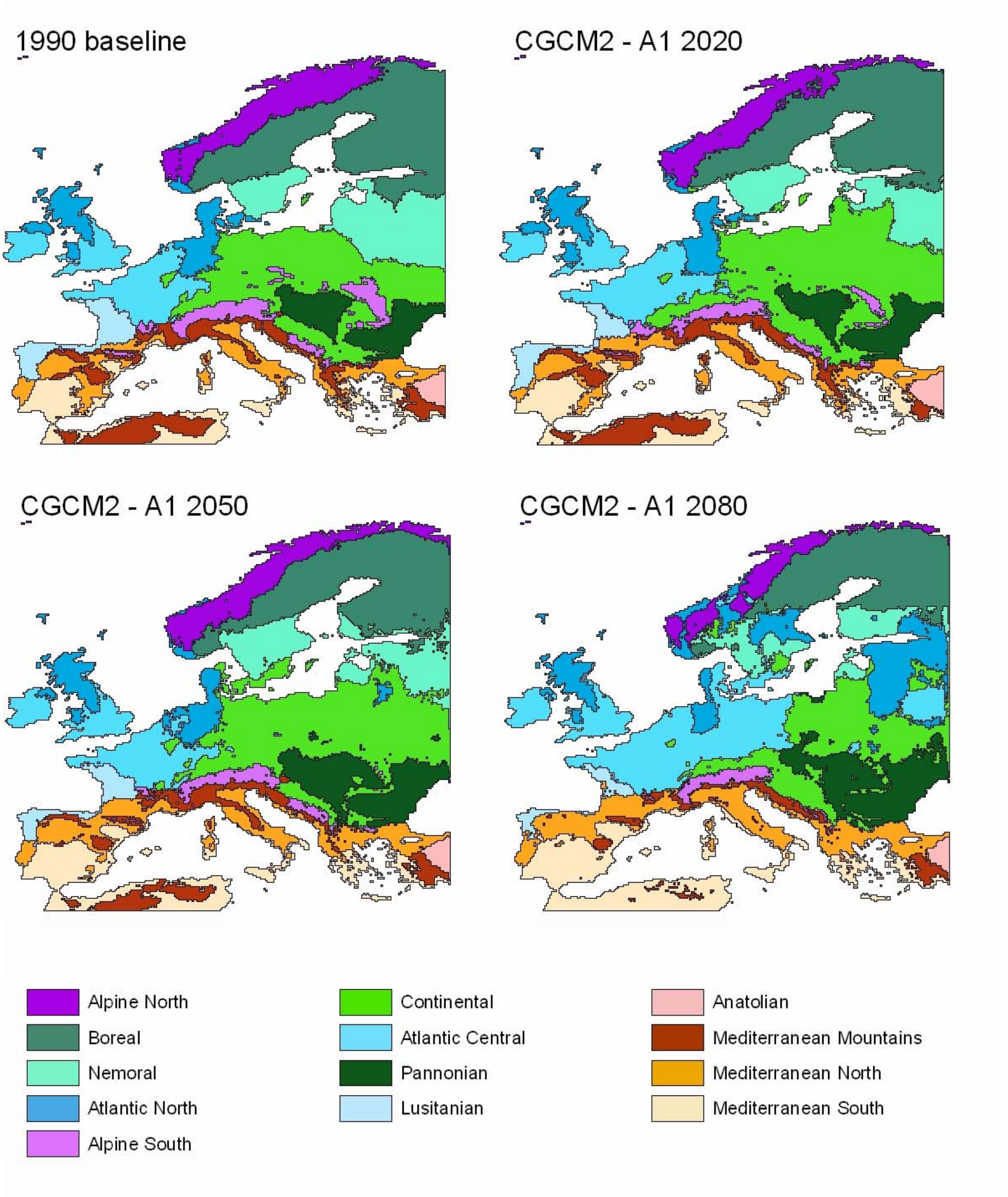

Figure CP12. Maps of shifting Environmental Zones for one climate change scenario (CGCM2 Global Climate Model ; A1 emission scenario).

Colour plate 13

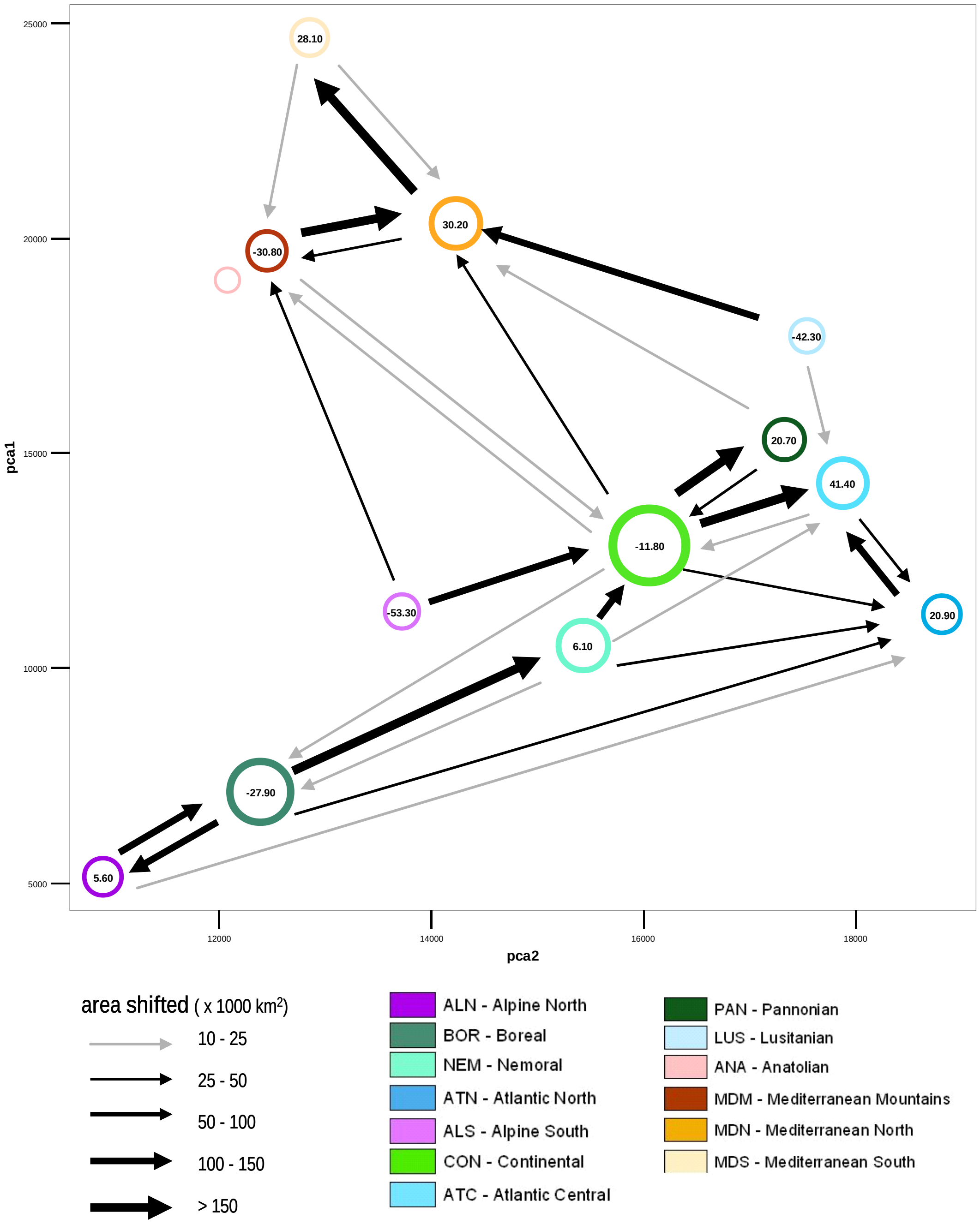

Figure CP13. Shifting Environmental Zones, summarized across 16 climate change scenarios, plotted in the environmental space of the classification variables of the *Environmental Stratification of Europe*. Arrows indicate the directions of projected shifts, and the shifting area, in square kilometres. Size of the circle represents the relative extent of the EnZs under baseline conditions. The numbers in the circle indicate mean change in extent of each EnZ, as a percentage. See also Table 6.1.

Colour plate 14

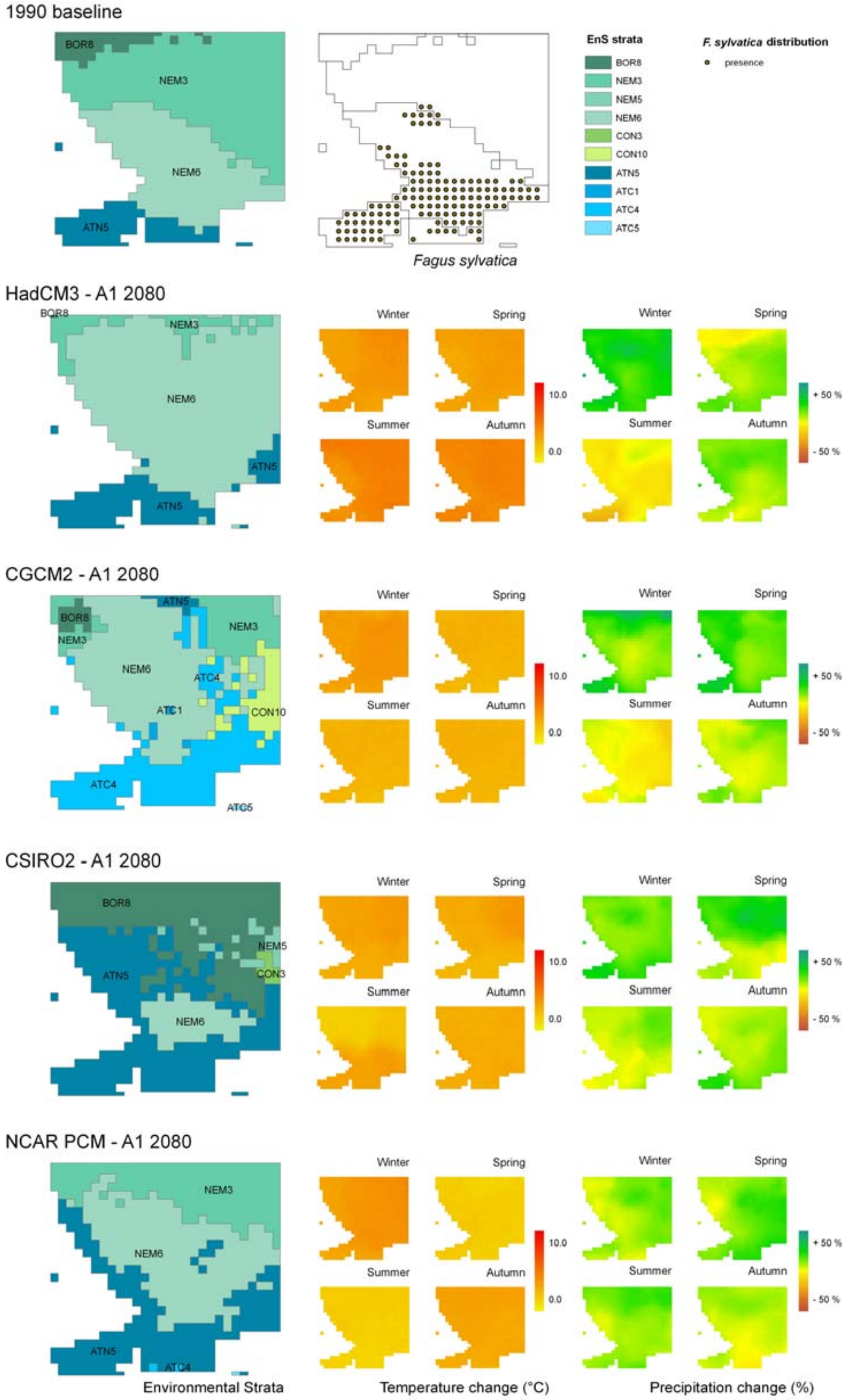

Figure CP14. Shifting environments and climate change in the Swedish sample region and the current distribution of *Fagus sylvatica* (Köble & Seufert, 2001).

Colour plate 15

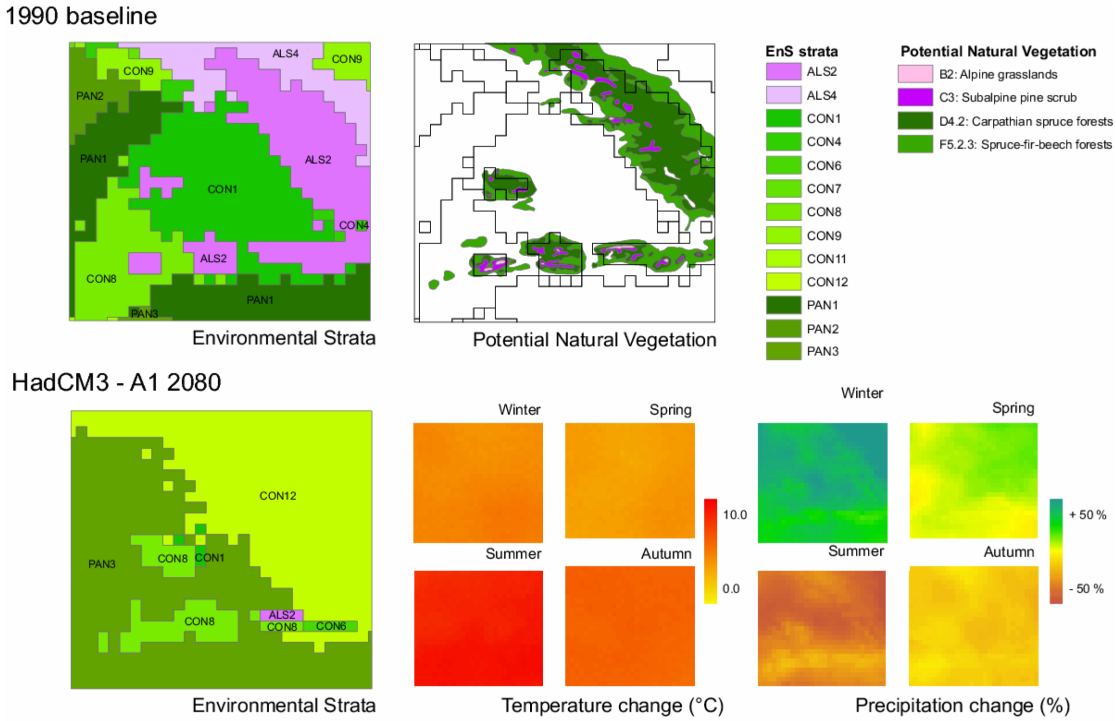

Figure CP15.1. Shifting environments and climate change in the Carpathian sample region and the Potential Natural Vegetation for the mountain range (Bohn *et al.*, 2000)

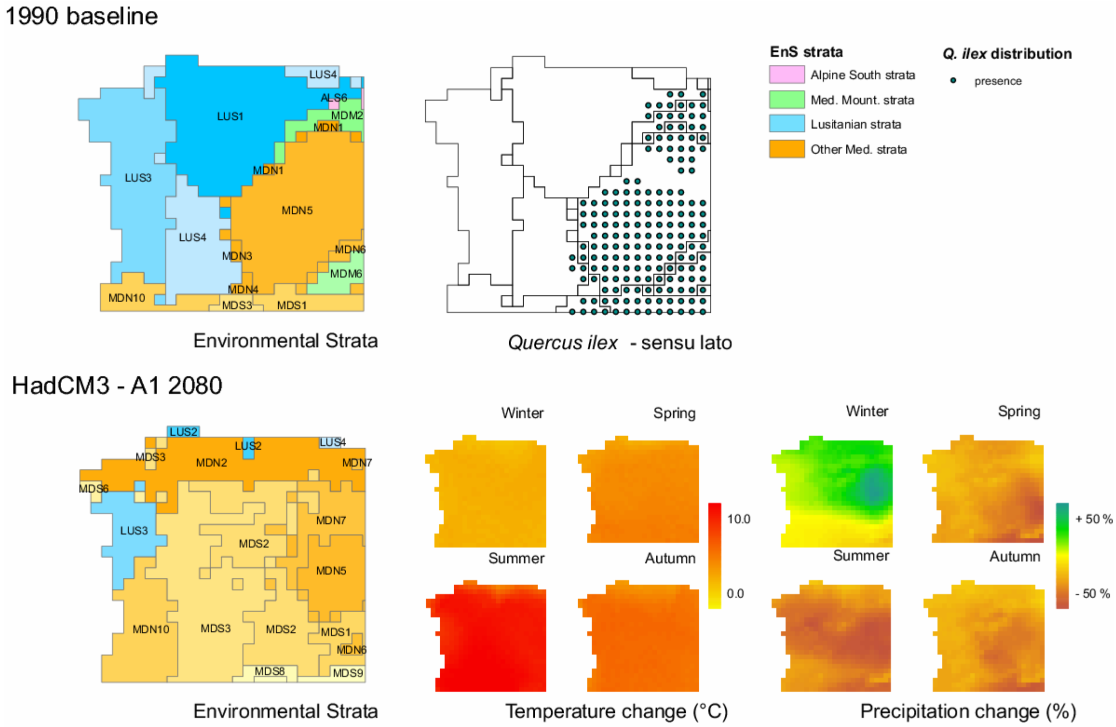

Figure CP15.2. Shifting environments and climate change in the sample region on the Iberian Peninsula and the current distribution of *Quercus ilex – senso lato* (Köble & Seufert, 2001).

Colour plate 16

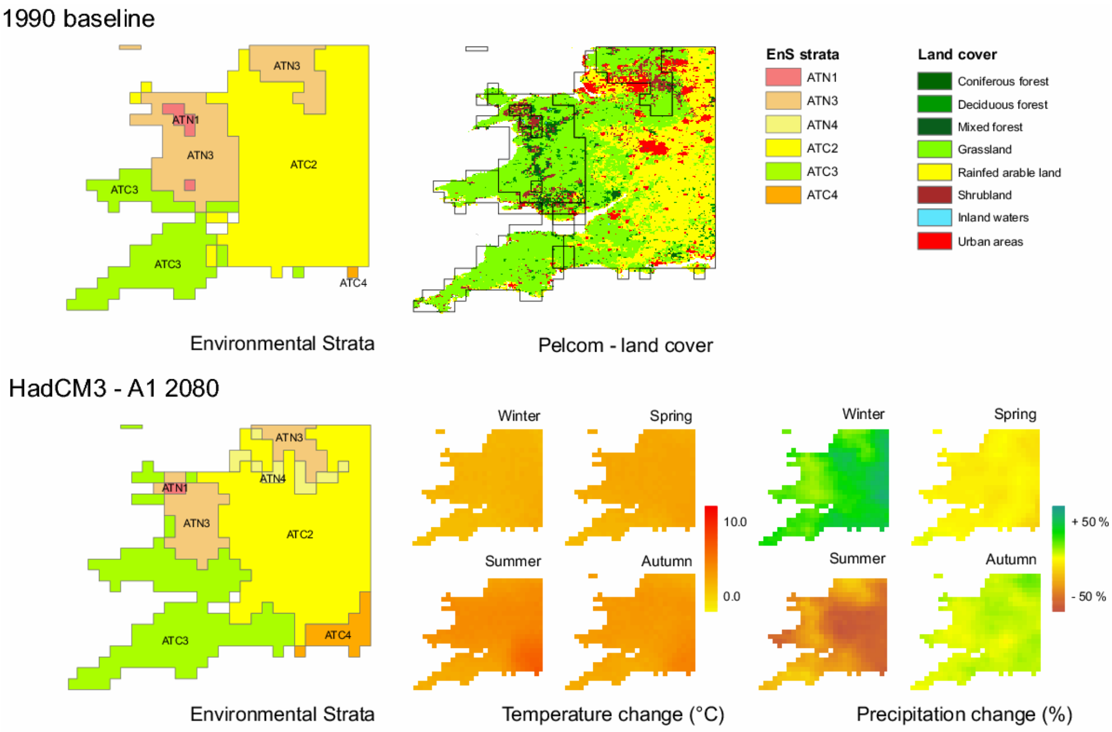

Figure CP16. Shifting environments and climate change in the English sample region and current land cover (PELCOM, Mücher *et al.*, 2001).

Summary

Wider context

Many aspects of our planet are changing rapidly because of to human activities and these changes are expected to accelerate during the next decades. For example, forest area in the tropics is declining, many species are threatened with extinction, and rising atmospheric carbon dioxide results in global warming. Many of these changes will have an immediate and strong effect on agriculture, forestry, biodiversity, human health and well-being, and on amenities such as traditional landscapes. Furthermore, a growing global population, with increasing per capita consumption of food and energy, are expected to continue emitting pollutants to the atmosphere, resulting in continued nitrogen deposition and eutrophication of environments. Over the last decades many people have become increasingly aware of these environmental changes, such that they are now commonly recognized as 'global change'. In the face of these changes, it is important to integrate and extend current operational systems for monitoring and reporting on environmental and social conditions. Many research projects and several environmental assessments are currently addressing these concerns at all relevant scales, frequently in multidisciplinary collaborations. However, integrating this wealth of information across disciplines remains a considerable challenge.

The vulnerability framework

This thesis presents and demonstrates a framework for integrating the results from the European project *Advanced Terrestrial Ecosystem Analysis and Modelling* (ATEAM) in a vulnerability assessment. ATEAM was a 3.4 million Euro project, involving scientists from 18 research institutes across the EU. Different modelling groups, specialised in disciplines such as agricultural science, forestry and biodiversity modelling, used the same, internally consistent, climate and land use change scenarios to calculate maps for a range of indicators (see Table 2.3). These indicators were defined in such a way that they can be seen as 'ecosystem services', i.e. benefits people obtain from ecosystems. These include timber production, climate regulation, biodiversity, and soil fertility. The model outputs covered the EU15 countries as well as Norway and Switzerland in maps with a 10 arcmin x 10 arcmin resolution (approximately 16 km x 16 km) and were calculated for baseline conditions and three future time slices (1990-2020, 2020-2050, 2050-2080).

These maps of ecosystem service provision give important insights of the potential impact of global change for the different sectors, but do not take into account the possibility of adaptation to these impacts, thus reducing vulnerability to global change. Furthermore, it is difficult to compare impacts between different regions and across sectors. The principal objective of this thesis was to develop a methodology for quantifying and mapping vulnerability to global change impacts for Europe. The vulnerability framework should integrate the results form the sectoral ecosystem models. It should allow for comparisons between ecosystem service indicators, between global change scenarios and between different regions. In addition, some measure of adaptive capacity will need to be incorporated. This resulting framework can help answer policy-relevant questions such as:

- Which regions are most vulnerable to global change ?
- How do the vulnerabilities of two regions compare ?
- Which sectors are the most vulnerable in a certain region ?
- Which scenario is the least harmful for a sector ?

In this thesis, vulnerability is defined as '*the degree to which an ecosystem service is sensitive to global change plus the degree to which the sector that relies on this service is unable to adapt to the changes*'. This definition includes the potential impact of global change on the human-environment system to global change, as well as the possibility to reduce these impacts by adaptation, thus reducing vulnerability.

The potential impacts are derived from the ATEAM ecosystem models. Increasing ecosystem service provision is defined as a positive potential impact (e.g. increased wood production), and *vice versa*. These measures of potential impacts are not easily compared. Firstly, the ecosystem service indicators are intrinsically different. Biodiversity and soil fertility are not easily compared. Furthermore, many ecosystem service indicators are very much related to wider environmental conditions, making it difficult to compare the potential impacts across the European environment. Wood production in The Netherlands and in Spain is difficult to compare because the environment in these countries differs so much. In order to overcome these problems, potential impacts are stratified by principal environments, thus creating a standardised measure of stratified potential impact that can be calculated for each ecosystem service indicator. The stratified potential impacts for the various ecosystem service indicators show that there are large potential impacts on the provision of many ecosystem services. The extent of these impacts differs between the ecosystem services, different regions of Europe and the alternative scenarios of change.

Adaptation in general is understood as an adjustment in natural or human systems in response to actual or expected environmental change, which moderates harm or exploits beneficial opportunities. Here, adaptive capacity reflects the potential to implement planned adaptation measures and is therefore concerned with deliberate human attempts to cope with change, and not with autonomous adaptation. For the ATEAM vulnerability framework a macro-scale indicator of adaptive capacity was constructed. This index was based on a conceptual framework of socio-economic indicators, determinants of and components of adaptive capacity, e.g. gross domestic product, female activity rate, equity and number of doctors. The index was calculated on a province level across the European Union and differs for each storyline. Different regions in Europe show different adaptive capacities. The lowest values occur in the Mediterranean, but differences decline over time.

For the final vulnerability maps the two component of vulnerability, the potential impacts and the adaptive capacity, have been combined visually. Complete integration was considered, but given the limited understanding of adaptive capacity it was felt that such a combination is not possible. Nevertheless, the vulnerability maps give an intuitive overview of the vulnerability to the provision of an ecosystem service. For more detailed analyses, the stratified potential impacts and the adaptive capacity indicator can be viewed separately. In order to facilitate such analyses, a separate piece of software was develop, the *ATEAM vulnerability mapping tool*, which is available on the CD-ROM annex to this thesis.

Results form the vulnerability assessment

On the whole, the Mediterranean region is projected to be the most vulnerable to global change. Large environmental shifts are projected, and the agriculture and nature conservation sectors face negative impacts. Forestry may be able to expand slightly, but faces negative impacts from droughts and forest fires. The only positive development for this region is a slight increase in net carbon storage. While adaptive capacity is indicated to increase, it is unlikely that the negative impacts can be alleviated fully by adaptation measures.

In the Atlantic region climate change impacts will be relatively minor because of buffering of the climate by the ocean. Land use change will affect this region, and especially the agricultural sector will face negative impacts. Nevertheless, this region, which includes wealthy countries such as

Denmark, United Kingdom and France, is indicated to have a high adaptive capacity. Vulnerability of the region will therefore be relatively low.

The vulnerability assessment shows how the alternative development pathways associated with the SRES storylines influence ecosystem service provision. The scenarios associated with strong economic developments and open markets (A-family) generally show the most negative impacts. There are however exceptions, for instance under the A1 scenario agricultural production is concentrated in the most optimal environments, and therefore for Denmark and The Netherlands A1 is the most favourable scenario. Interestingly, the A-family of economic scenarios is also associated with the most rapid development of the adaptive capacity indicator, thus reducing vulnerability.

Limitations and relevance

The vulnerability framework presented in this thesis forms an extra extension to modelled projections of ecosystem service provision under future scenarios of global change. It is therefore inevitable that within the vulnerability framework complexity and uncertainty is increased. Importantly, the additional assumptions within the vulnerability framework have been made explicit. While the main motivation for the development of vulnerability framework was the demand for methods to integrate multidisciplinary assessments, such integration comes at the price of additional uncertainty.

A second limitation of the vulnerability framework is the simple adaptive capacity index. It was developed specifically for the ATEAM vulnerability framework, with great constraints on time and resources. While it provides the possibility to include adaptive capacity in the vulnerability framework, the adaptive capacity index can only be seen as a very generic and coarse indicator. A single indicator is used for all sectors, across the whole of Europe.

Despite its limitations the results from the vulnerability assessment confirm existing knowledge about projected global change impacts in Europe. While stratification of the ecosystem service provision facilitates comparisons between regions. Nevertheless, stakeholders interested in a specific sector, or region have indicated that the uncertainties in the projections, combined with difficulties in relating results to their regional situation, limits the usefulness of the assessment in policy development.

The results provided by this assessment could nevertheless be useful to stakeholders who are interested in multidisciplinary global change issues at the European level, e.g. EU policymakers and representatives from international NGOs. They can use the maps of ecosystem service provision, potential impacts and vulnerability as a spatially explicit portfolio of alternative futures. The provision of ecosystem services can be seen in their interactions, sometimes competing with each other, sometimes erasing or enforcing each other. While such a portfolio is not suitable for direct policy development, it can form a suitable basis for discussion on future policy directions, thereby facilitating sustainable management of Europe's natural resources.

Final conclusions

The final conclusions of the research present in this thesis are:

1. Global change will have a large influence on ecosystem service provision in Europe.

2. There is large heterogeneity in projected vulnerability between regions and ecosystem services.

3. The Mediterranean region is projected to be the most vulnerable, with greatest impacts and lowest indicated adaptive capacity.

4. Wealthy north-western European countries face the lowest impacts and are indicated to have the greatest adaptive capacity.

5. On the whole, the agriculture and nature conservation sectors are projected to be most vulnerable.

6. The presented vulnerability framework is useful for stimulating discussion, and illustrating how vulnerability is influenced by future development pathways.

Samenvatting

Bredere context

Menselijke activiteiten veranderen het aanzien van de aarde. Deze veranderingen zullen in de komende decennia versnellen. Tropische bossen verdwijnen, veel soorten worden met uitsterven bedreigd en stijgende koolstofdioxide concentraties leiden tot klimaatsveranderingen. Veel van deze veranderingen zullen een directe invloed hebben op landbouw, bosbouw, natuurbeheer, gezondheid en welzijn. De groeiende wereldbevolking, met een toenemende voedsel- en energieconsumptie, zal waarschijnlijk ook de atmosfeer blijven vervuilen, wat leidt tot aanhoudende stikstof depositie en eutroficatie. In de afgelopen decennia zijn steeds meer mensen zich bewust geworden van de samenhang tussen al deze veranderingen, zodat ze tegenwoordig erkend worden als '*global change*' (i.e. mondiale milieuveranderingen). Om deze veranderingen goed in kaart te brengen is het belangrijk om bestaande assessments, van zowel ecosystemen als maatschappelijke ontwikkelingen, te combineren en integreren. Op dit moment zijn veel multidisciplinaire onderzoeken en verkenningen gericht op dergelijke ontwikkelingen, op alle relevante schaalniveaus. Het integreren van deze informatie blijft echter een grote uitdaging.

Het kwetsbaarheidraamwerk

Dit proefschrift presenteert en demonstreert een raamwerk voor het integreren van de resultaten van het Europese onderzoeksproject *Advanced Terrestrial Ecosystem Analysis and Modelling* (ATEAM) in een kwetsbaarheids assessment. In ATEAM namen vele wetenschappers uit 18 onderzoeksinstituten deel. De verschillende modelleergroepen, gespecialiseerd in verschillende sectoren zoals landbouw, bosbouw en biodiversiteit, gebruikten dezelfde klimaat- en landgebruikscenario's om de ruimtelijke patronen voor een reeks indicatoren te berekenen. Deze waren zo gedefinieerd dat ze gezien kunnen worden als 'ecosysteem diensten'. Ecosysteem diensten zijn het indirecte of directe nut dat mensen halen uit ecosystemen. Voorbeelden hiervan zijn: voedsel- en houtproductie, klimaatregulering, biodiversiteit en bodemvruchtbaarheid. De ATEAM modellen berekenden de patronen met een 10 arcmin x 10 arcmin resolutie (ongeveer 16 km x 16 km) voor de EU15 landen, Noorwegen en Zwitserland. Deze resulterende kaarten werden berekend voor de huidige situatie en drie toekomstige perioden (1990-2020, 2020-2050, 2050-2080).

De kaarten met de veranderingen in ecosysteem diensten geven belangrijke inzichten in de potentiële effecten van wereldwijde milieuveranderingen op verschillende sectoren, maar houden geen rekening met de mogelijkheid dat sectoren door aanpassingen negatieve effecten kunnen voorkomen, en zo hun kwetsbaarheid kunnen verminderen. Verder is het moeilijk om de potentiële effecten van verschillende sectoren en regio's met elkaar te vergelijken.

Het hoofddoel van dit proefschrift is om een methode te ontwikkelen om kwetsbaarheid voor mondiale milieuveranderingen te kwantificeren en in kaart te brengen voor Europa. Het kwetsbaarheidraamwerk moet de resultaten van de sectorale modellen integreren. Het moet vergelijkingen tussen indicatoren, scenario's en regio's mogelijk maken. Ten slotte, moeten ook de aanpassingsmogelijkheden om negatieve effecten te beperken expliciet worden opgenomen. Het raamwerk kan dan helpen om beleidsrelevante vragen te beantwoorden, zoals:

- Welke regio's zijn het meest kwetsbaar voor mondiale veranderingen?
- Wat is het verschil in kwetsbaarheid tussen twee regio's?
- Welke sectoren zijn het meest kwetsbaar in een bepaalde regio?
- Welk scenario is het minst schadelijk voor een sector?

In dit proefschrift is kwetsbaarheid gedefinieerd als '*de mate waarin een ecosysteem dienst gevoelig is voor mondiale milieuveranderingen, en de mate waarin de sector die afhankelijk is van die dienst zich niet kan aanpassen aan die veranderingen*'. Deze definitie omvat de potentiële effecten van mondiale milieuveranderingen op de interactie tussen de mens en haar leefomgeving, alsmede de mogelijkheid om deze effecten te vermijden, en dus kwetsbaarheid te verlagen, door zich aan te passen.

De potentiële effecten worden afgeleid van de ATEAM modellen. Toename van een ecosysteem dienst wordt gezien als een positief effect (b.v. hogere houtopbrengst), en *vice versa*. Veranderingen in deze indicatoren kunnen niet vergeleken worden omdat de indicatoren intrinsiek van elkaar verschillen: biodiversiteit en bodemvruchtbaarheid zijn moeilijk te vergelijken. Verder zijn veel van deze indicatoren sterk gecorreleerd met bredere omgevingsfactoren, waardoor het moeilijk is om vergelijkingen te maken tussen uiteenlopende gebieden. Zo is bijvoorbeeld houtproductie in Nederland niet te vergelijken met houtproductie in Spanje omdat het klimaat, de boomsoorten en de opbrengst zo sterk verschillen. Deze problemen kunnen voorkomen worden door de indicatoren te stratificeren over verschillende omgevingsklassen. Deze gestratificeerde waarden van de potentiële effecten voor ecosysteem diensten vormen gestandaardiseerde waarden die berekend kunnen worden voor iedere kaart van ecosysteem diensten. De kaarten van gestratificeerde potentiële effecten voor diverse ecosysteem diensten laten zien dat er grote potentiële effecten zijn. De mate van deze effecten verschilt tussen ecosysteem diensten, regio's en de veranderingscenario's. De gebruikte scenario's zijn gebaseerd op de SRES scenario's van het IPCC.

Onder adaptatie wordt meestal een aanpassing in natuurlijke of menselijke systemen verstaan, als respons op daadwerkelijke of verwachte milieuveranderingen, om schade te beperken of nieuwe mogelijkheden te benutten. In dit proefschrift geeft aanpassingsvermogen de potentiële mogelijkheid aan van sectoren om adaptatie strategieën te implementeren. Het gaat dus niet om een autonome adaptatie, maar om bewuste pogingen om negatieve effecten te verminderen. Gebaseerd op een conceptueel raamwerk van relevante socio-economische indicatoren is een geaggregeerde indicator ontwikkeld voor aanpassingsvermogen die past binnen het kwetsbaarheidraamwerk van ATEAM. Voorbeelden van de gebruikte deelindicatoren zijn: bruto nationaal product, gelijkheid, aantal werkende vrouwen en aantal artsen. De indicator is berekend op provincieniveau voor EU15, Zwitserland en Noorwegen en is gekoppeld aan de verschillende scenario's. Aanpassingsvermogen verschilt per regio. De laagste waarden worden in het Middellandse-Zeegebied gevonden, maar in de toekomst worden deze verschillen kleiner in de meeste scenario's.

Voor de uiteindelijke kwetsbaarheidkaarten worden de twee componenten van kwetsbaarheid, de potentiële effecten en het aanpassingsvermogen, visueel gecombineerd. Volledige integratie is overwogen, maar gegeven het beperkte begrip van adaptatie is dit niet haalbaar. Toch geven de kwetsbaarheidkaarten een intuïtief overzicht van kwetsbaarheid voor veranderingen in ecosysteem diensten. Voor meer gedetailleerde analyses kunnen de indicatoren voor potentiële effecten en aanpassingsvermogen apart worden bekeken. Om zulke analyses te ondersteunen is een speciaal computerprogramma ontwikkeld, de *ATEAM vulnerability mapping tool*, dat beschikbaar is op de CD-ROM achterin dit proefschrift.

Resultaten van de kwetsbaarheidassessment

In Europa is het Middellandse-Zeegebied is het meest kwetsbaar voor mondiale milieuveranderingen. Er worden hier grote verschuivingen voorspeld, zowel voor klimaat als landgebruik, die met name voor landbouw en natuurbescherming grote gevolgen zullen hebben. Bosbouw kan zich wellicht wat uitbreiden, maar ondervindt negatieve effecten van droogten en bosbranden. De enige positieve ontwikkeling voor dit gebied is een lichte toename in koolstofvastlegging. Hoewel het aanpassingsvermogen toe zal nemen is het onwaarschijnlijk dat de negatieve effecten volledig gecompenseerd kunnen worden door adaptatie.

In de Atlantische regio zullen effecten van klimaatverandering relatief gering zijn door een sterke buffering van de oceaan. Landgebruikverandering zal de regio beïnvloeden, en vooral de landbouwsector zal enige negatieve effecten ondervinden. Desalniettemin zal deze regio, met rijke landen als Denemarken, het Verenigd Koninkrijk en Frankrijk, een hoog aanpassingsvermogen hebben. De kwetsbaarheid is hierdoor relatief gering.

De kwetsbaarheidassessment laat zien dat de ontwikkelingsrichtingen van de SRES scenario's de potentiële effecten beïnvloeden. Het scenario dat de grootste economische ontwikkeling voorspelt (A1) heeft meestal de meest negatieve effecten tot gevolg. Er zijn echter uitzonderingen. Voor de landbouw sector in Denemarken en Nederland vormt is A1 scenario het gunstigst, omdat landbouw geconcentreerd wordt in de meest productieve gebieden. Verder leiden de economische georiënteerde scenario's tot de hoogste waarden van de adaptatie-index, waardoor kwetsbaarheid verlaagd wordt.

Beperkingen en relevantie

Het kwetsbaarheidraamwerk geeft een extra dimensie aan de gemodelleerde projecties van ecosysteem diensten onder scenario's van mondiale milieuveranderingen. Het is onvermijdelijk dat door deze extra stap de complexiteit wordt vergroot en onzekerheid toeneemt. Het is echter belangrijk dat de extra stappen binnen het kwetsbaarheidraamwerk expliciet zijn gemaakt. De doelstelling van dit onderzoek was om de verschillende onderdelen van een multidisciplinair assessment te integreren. Het is belangrijk te beseffen dat een dergelijke integratie gepaard gaat met een grotere complexiteit en onzekerheid .

Een tweede beperking vormen de simpele aannames voor het toekomstige aanpassingsvermogen. Het gebruikte geaggregeerde indicatormodel is speciaal voor dit onderzoek ontwikkeld, met beperkte middelen en aanzienlijke tijdsdruk. Hoewel het de mogelijkheid geeft aanpassingsvermogen in het raamwerk op te nemen, blijft het een zeer algemene benadering. Een enkele indicator wordt gebruikt voor alle sectoren over heel Europa. Verschillende belanghebbenden hebben aangegeven dat zij het aanpassingsvermogen voor hun regio of sector zelf beter kunnen inschatten dan de geaggregeerde indicator.

Ondanks deze beperkingen bevestigen de resultaten van het kwetsbaarheidassessment de bestaande kennis over de effecten van mondiale milieuveranderingen in Europa. De stratificatie maakt meer gedetailleerde analyses tussen regio's mogelijk. Maar de onzekerheden in de voorspellingen kunnen in het bijzonder voor belanghebbenden van specifieke sectoren of regio's het nut van de resultaten sterk beperken.

De resultaten van deze assessment nuttig zijn belanghebbenden die geïnteresseerd zijn in multidisciplinaire vraagstukken op Europese schaal, zoals Europese beleidsmedewerkers en afgevaardigden van internationale niet-gouvernementele organisaties (NGOs). Zij kunnen de kaarten met ecosysteem diensten, potentiële effecten en kwetsbaarheid gebruiken als een ruimtelijk expliciet portfolio van alternatieve toekomsten. Ecosysteem diensten kunnen bestudeerd worden in hun onderlinge interacties. Hoewel een dergelijk portfolio niet direct geschikt is voor het ontwikkelen van beleid, kan het een goede basis vormen voor discussie over duurzaam beheer van natuurlijke hulpbronnen.

Conclusies

De voornaamste conclusies van dit proefschrift zijn:

1. Mondiale milieuveranderingen hebben een grote invloed op ecosysteem diensten in Europa.

2. Er is grote heterogeniteit in voorspelde kwetsbaarheid tussen regio's en ecosysteem diensten.

3. Het Middellandse-Zeegebied is het meest kwetsbaar, met de grootste potentiële effecten en het laagste aanpassingsvermogen.

4. De rijke landen in noordwest Europa zijn het minst kwetsbaar, met de laagste potentiële effecten en het grootste aanpassingsvermogen.

5. In het geheel genomen zijn de sectoren 'landbouw' en 'natuurbescherming' het meest kwetsbaar.

6. Het kwetsbaarheidraamwerk is een nuttig middel om discussie te stimuleren over hoe kwetsbaarheid beïnvloed kan worden door verschillende richtingen van toekomstige ontwikkelingen.

Curriculum Vitae

Marc Metzger was born and raised in Nijmegen. For many years he was actively involved in a local Scout group, including five years leading a team of adults in organizing activities and camping trips for different age-groups. Here he adopted the motto: 'Search for the bends in the straight path.' Set out a direction, make a plan, persist in getting there, but at the same time enjoy the journey.

During his biology study Marc became interested in the interaction between abiotic, biotic and cultural components determining landscapes, habitats and biodiversity. This resulted in a full year of research at the Wageningen research institute *Alterra*, assessing the potential for Dutch nature target types in a catchments area in The Netherlands. Expert rules were combined with hydrological scenarios and soil information to explore potential distribution of vegetation types and habitats.

Having enjoyed the independence and challenge of conducting research, Marc decided to pursue an academic career. The PhD position within the EU project ATEAM appealed to him because it would allow him to work in a multidisciplinary and international environment. Within the project, Marc enjoyed working with scientists and stakeholders from different disciplines, sometimes struggling to find common ground, but usually succeeding in the end.

A major component of his PhD work consisted of synthesizing outputs from a suite of ecosystem models for biodiversity, agriculture, forestry, hydrology and vegetation. Outputs were analysed for alternative scenarios of global change and summarized for different regions of Europe. Marc coordinated the development of an interactive CD-ROM containing the results from the ATEAM project. Scientific publications are currently in press.

An unexpected element in his PhD was the intensive collaboration with landscape ecologists form *Alterra*, developing a statistically derived classification of the European environment. Their use for the stratification would be to place field observations in a European context. This collaboration has led to an increased insight that the current top-down assessments need to be linked to more detailed regional or field processes. This could be accomplished by placing randomly selected regional samples in a European context.

Publication list

Peer-reviewed publications

Ewert F, Rounsevell MDA, Reginster I, Metzger MJ, Leemans R (2005) Future scenarios of European agricultural land use. I: Estimating changes in crop productivity. Agriculture Ecosystems and Environment 107: 101-116.

Schröter D, Metzger MJ, Cramer W, Leemans R (2005) Vulnerability assessment – analysing the human-environment system in the face of global environmental change. The ESS bulletin 2: 11- 17.

Metzger MJ, Bunce RGH, Jongman RHG, Mücher CA, Watkins JW (2005). A climatic stratification of the environment of Europe. Global Ecology and Biogeography. In press.

Metzger MJ, Leemans R, Schröter DS (2005) A multidisciplinary multi-scale framework for assessing vulnerability to global change. International Journal of Applied Geo-information and Earth Observation. In press.

Metzger MJ, Rounsevell MDA, Leemans R, Schröter D (2005) The vulnerability of ecosystem services to land use change. Agriculture Ecosystems and Environment. In press.

Jongman RHG, Bunce RGH, Metzger MJ, Mücher CA, Howard DC, Mateus VL (2005) Objectives and applications of a statistical environmental stratification of europe. Landscape Ecology. In press.

Rounsevell MDA, Reginster I, Araújo MB, Carter TR, Dendoncker N, Ewert F, House JI, Kankaanpää S, Leemans R, Metzger MJ, Schmit C, Smith P, Tuck G (2005) A coherent set of future land use change scenarios for Europe. Agriculture Ecosystems and Environment. In press.

Verboom J, Alkemade LRM, Klijn J, Metzger MJ, Reijnen R (2005) EURURALIS: Biodiversity modelling for land-use change scenrios for EU25 countries. Ecological Economics. In press.

Non-peer reviewed papers, proceedings and reports

Bunce RGH, Groom GB, Jongman RHG, Padoa-Schippa E, Bogers M, Blust G de, Brandt J, Elena-Rosselló R, Hofer G, Ispikoudis I, Kovář P, Metzger M, Mücher C, Paelinckx D, Palo A, Perez-Soba M, Ramos I, Roche P, Pasta S, Peterseil J, Skånes H, Wrbka T (2005) Handbook for Surveillance and Monitoring of European Habitats. 1st Edition. Alterra Wageningen UR, Wageningen, The Netherlands.

Ewert F, Rounsevell M, Reginster I, Metzger M, Leemans R (2005). Technology development and climate change as drivers of future agricultural land use. In: Brouwer F, McCarl B eds. Rural land, agriculture and climate beyond 2015. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Metzger MJ, Leemans R, Schröter D, Cramer W, and the ATEAM consortium (2004) The ATEAM vulnerability mapping tool. Quantitative Approaches in Systems Analysis No. 27, CD-ROM publication, Office C.T. de Wit Graduate School for Production Ecology & Resource Conservation (PE&RC), Wageningen, The Netherlands. [Available on the CD-ROM annex to this thesis]

Schröter D, Acosta-Michlik L, Arnell AW, Araújo MB, Badeck F, Bakker M, Bondeau A, Bugmann H, Carter T, Vega-Leinert AC de la, Erhard M, Espiñeira GZ, Ewert F, Friedlingstein P, Fritsch U, Glendining M, Gracia CA, Hickler T, House J, Hulme M, Klein RJT, Krukenberg B, Lavorel S, Leemans R, Lindner M, Liski J, Metzger MJ, Meyer J, Mitchell T, Mohren F, Morales P, Moreno JM, Reginster I, Reidsma P, Rounsevell MDA, Pluimers J, Prentice IC, Pussinen A, Sánchez A, Sabaté S, Sitch S, Smith B, Smith J, Smith P, Sykes MY, Thonicke K, Thuiller W, Tuck G, Werf G van der, Vayreda J, Wattenbach M, Wilson DW, Woodward FI, Zaehle S, Zierl B, Zudin S, Cramer W (2004) The ATEAM final report 2004 – Detailed report related to overall project duration. Advanced Terrestrial Ecosystem Analysis and Modelling, a project funded under the 5th framework Programme of the European Union. [http://www.pik-potsdam.de/ateam/]

Ewert F, Rounsevell M, Reginster I, Metzger M, Kamphorst K, Leemans R (2003) Estimating changes in primary productivity and effects on agricultural land use. Book of abstracts, International workshop 'COST 627, Carbon sequestration opportunities in European grassland: Mitigation scenarios at plot, farm and regional scale'. 7-8 September 2003, INRA, Clermont-Ferrand, France.

Schröter D, Acosta-Michlik L, Reidsma P, Metzger M, Klein RJT (2003) Modelling the Vulnerability of Eco-Social Systems to Global Change: Human Adaptive Capacity to Changes in Ecosystem Service Provision. Pages 4 in 5th Open Meeting of the Human Dimensions of Global Environmental Change Research Community, Montreal, Canada.

Metzger M, Bunce B, Jongman R, Mateus V, Mücher S (2003) The Environmental Classification of Europe, a new tool for European landscape ecologists. Landschap 20: 50-54.

Mücher CA, Bunce RGH, Jongman RHG, Klijn JA, Koomen A, Metzger MJ, Wascher DM (2003) Identification and Characterisation of Environments and Landscapes in Europe. Alterra rapport 832. Alterra, Wageningen UR, Wageningen, The Netherlands.

Mücher CA, Roerink GJ, Metzger MJ (2003) Study of vegetation dynamics in relation to climate parameters. In: Estreguil C, Maggi M, Clevers J, Vliet A van (eds) Proceedings International Workshop 'Use of Earth Observation Data for Phenological Monitoring', 12-12 December 2002. JRC, Ispra, Italy, pp 83-87.

Metzger MJ, Leemans R, Schröter D (2004) A multidisciplinary multi-scale framework for assessing vulnerabilities to global change. Proceedings of Millennium Assessment Conference: Bridging Scales and Epistemologies, Alexandria, 17 – 20 March 2004.

Metzger MJ (2000) Abiotische kansrijkdom voor natuurdoeltypen; de haalbaarheid van natuurdoelen in het stroomgebied van de Beerze en de Reusel. Alterra rapport 042. Alterra, Wageningen UR, Wageningen, The Netherlands.

PE&RC PhD Education Statement Form

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 22 credits (= 32 ECTS = 22 weeks of activities)

Review of literature (4 credits)

- Mapping vulnerability of ecosystem services (2001)

Post-Graduate Courses (5 credits)

- Spatial modelling in ecology (2002)
- Modelling techniques & systems engineering (2002)
- Summer School 'Integrated Assessment of vulnerable ecosystems under global change' (2003)

Deficiency, Refresh, Brush-up and General Courses (3.6 credits)

- Basic and advanced statistics (2001)
- ArcView 8 (ArcGIS) (2004)
- Multivariate Analysis (2005)

PhD discussion groups (4 credits)

- Statistics, maths and modelling in production ecology and resource conservation (2001-2005)

PE&RC Annual Meetings, Seminars and Introduction Days (1.8 credits)

- PE&RC Science Day: 'Food Insecurity' (2001)
- Final symposium NOP-II: Dutch climate change programme (2001)
- PE&RC Science Day 'Ethics in Science' (2002)
- WLO symposium for Young Landscape Ecologists (2003)
- PE&RC Science Day 'Global Change and Biodiversity' (2003)
- PCCC symposium 'Europa in de broeikas' (2004)
- PE&RC Science Day 'Biological Disasters' (2004)
- PE&RC Scientific Publishing workshop (2004)
- WUR-CGI symposium 'Trends in Geo-Information' (2004)

International symposia, workshops and conferences (9.9 credits)

- ATEAM start-up collaboration meeting and stakeholder meeting Isle-sur-la-Sorgue, France (2001)
- Times are a changin' Phenology conference (2001)
- 1st ATEAM annual collaboration meeting, Barcelona, Spain (2002)
- ATEAM vulnerability workshop, Potsdam, Germany (2002)
- 2nd ATEAM stakeholder meeting, Potsdam, Germany (2002)
- ATEAM Adaptive Capacity workshop, Louvain-la-Neuve, Belgium (2002)
- 2nd ATEAM annual collaboration meeting, Evora, Portugal (2003)
- International Association for Landscape Ecology World Congress, Crossing frontiers, Darwin, Australia (2003)
- BIOPRESS brainstorm workshop Biodiversity Change (2004)
- Millennium Assessment Conference: Bridging Scales and Epistomologies Alexandria, Egypt (2004)
- ATEAM final collaboration meeting, Annot, France (2004)
- 3rd ATEAM stakeholder workshop, Potsdam, Germany (2004)
- Workshop on Global Change and the Future of Ecosystems in Europe, Copenhagen, Denmark (2004)
- International Association for Landscape Ecology European Congress, Landscape Ecology in the Mediterranean, Faro, Portugal (2005)

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Material on CD-ROM annex

The CD-ROM annex contains the following supplementary files:

- a pdf file of this thesis
- the installation files and manual of the *ATEAM vulnerability mapping tool*
- the ESRI shapefile of the *Environmental Stratifictaion of Europe*, and other supplementary files