The ATEAM vulnerability mapping tool

M.J. Metzger, R. Leemans, D. Schröter, W. Cramer,
and the ATEAM consortium

Explore the vulnerability of different sectors to global change impacts in Europe.

Quantitative Approaches
in Systems Analysis No.27
December 2004

Quantitative Approaches in Systems Analysis

The Quantitative Approaches in Systems Analysis series provides a platform for publication and documentation of simulation models, optimization programs, Geographic Information Systems (GIS), expert systems, data bases, and utilities for the quantitative analysis of agricultural and natural systems. The series enables staff members, students and visitors of PE&RC to publish, beyond the constraints of refereed journal articles, updates of models, extensive data sets used for validation and background material to journal articles, workshops, conferences and seminars. The QASA series thus serves to support peer reviewed articles published elsewhere. The inclusion of listings of programs in an Appendix is encouraged. The sole responsibility for the contents of the reports, the use of correct language and lay-out rests with the authors.

Address of editorial board (for submitting manuscripts):

Office C.T. de Wit Graduate School for Production Ecology & Resource Conservation (PE&RC)
Haarweg 333
NL-6709 RZ Wageningen
The Netherlands
Phone: 31(0).317.485116/485414
Fax: 31(0).317.485572
E-mail: Office.PE@wur.nl

PE&RC

Quantitative Approaches in Systems Analysis is issued by The C.T. de Wit Graduate School for Production Ecology & Resource Conservation (PE&RC). PE&RC is a collaborative research and PhD/postdoctoral training institution of Wageningen University (WU). The mission of the school is:

Understanding the functioning of (agro-)ecosystems to enable the development of sustainable and multifunctional production- and land use systems.

The major objectives of the school are:

- The co-ordination and development of fundamental/strategic, disciplinary and interdisciplinary scientific research on issues related to both the agricultural and natural components of the rural environment.
- The co-ordination and development of post-graduate education. The educational programme of PE&RC aims at both acquiring in-depth knowledge of specific research issues, as well as broadening the student's scientific scope and integrating their own work in other research areas.

The school now involves 22 research groups with approximately 270 ongoing PhD projects. More information can be found at http://www.dpw.wageningen-ur.nl/peenrc/index.htm.

The ATEAM vulnerability mapping tool

M.J. Metzger, R. Leemans, D. Schröter, W. Cramer,
and the ATEAM consortium

Quantitative Approaches
in Systems Analysis No.27
December 2004

BIBLIOGRAPHIC DATA

M.J. Metzger, R. Leemans, D. Schröter, W. Cramer, and the ATEAM consortium

The ATEAM vulnerability mapping tool
Quantitative Approaches in Systems Analysis; no. 27
ISBN 90-6754-933-9
NUGI 834

Abstract
Terrestrial ecosystems provide a number of vital services for people and society, such as biodiversity, food, fibre, water purification, carbon sequestration, and recreation. The future capability of ecosystems to provide these services is determined by changes in socio-economic trends, land use, biodiversity, atmospheric composition and climate. The primary objective of the project ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling) was to assess the vulnerability of human sectors relying such ecosystem services. Within ATEAM a full suite of ecosystem models, covering biodiversity, agriculture, forestry, hydrology, and carbon sequestration were run for the same internally consistent scenarios of alternative futures. Each model gives insights into specific ecosystems and ecosystem services. Moreover, by combining and integrating the results in ATEAM's Vulnerability Assessment, more complex queries on series of ecosystems and ecosystem services can be answered as well. This report acts as a background document to the ATEAM Vulnerability Mapping Tool provided on the CD-rom.
This software acts as a digital atlas of the many maps created by the ATEAM project, giving both the scientific community and other stakeholders access to the project's results. Besides generating fact sheets containing both maps and background information, the tool also includes some simple analysis functionality. This report contains a summary of the ATEAM project, a manual to the mapping tool, guidelines for interpreting scenarios and potential impacts and an explanation of the ATEAM vulnerability framework.

Keywords
Vulnerability assessment; global change; ecosystem services; adaptive capacity

Guidelines for 'Quantitative Approaches in Systems Analysis'

- Manuscripts or suggestions should be submitted to the editorial board together with the names of at least two possible referees. The submission letter should indicate the scope and aim of the manuscript (e.g. to support scientific publications in journals, program manual, educational purposes).
- The editorial board determines the relevance of the topic to the series and (if published) approves the referees.
- The manuscripts (in English) are reviewed by two external referees. Referees will be contacted by the authors. The review process includes assessing the following: overall scientific soundness, clear structure and presentation, and completeness of the presented material(s).
- Depending on the referee comments the manuscript will be changed.
- The manuscript together with the referee reports and a letter of the authors explaining what has been done with the referee comments is sent to the editorial board.
- The editorial board evaluates manuscripts on language and lay-out matters in a general sense and takes a decision about publication.

The sole responsibility for the contents of the reports, the use of correct language and lay-out rests with the authors. The final version of the manuscripts should be delivered to the editors camera-ready for reproduction. The costs of printing and mailing are paid by the authors. Five copies should be sent to the office of PE&RC. Overall guidelines for the format of the texts, figures and graphs can be obtained from the PE&RC office.

Acknowledgements

The ATEAM Vulnerability Mapping Tool synthesises the main outputs of the EU 5th framework program EVK2-2000-00075 “Advanced Terrestrial Ecosystem Analysis and Modelling” (ATEAM). Many scientists contributed, both directly and indirectly, to the creation of the tool. References to key publication concerning scenarios, ecosystem models, and vulnerability concept used in ATEAM can be found both in the software and are listed below.

Here we acknowledge the contribution of all members of the ATEAM consortium: L. Acosta-Michlik, A.W. Arnell, M.B. Araújo, F. Badeck, M. Bakker, A. Bondeau, H. Bugmann, T. Carter, W. Cramer, A.C. de la Vega-Leinert, M. Erhard, G.Z. Espiñeira, F. Ewert, U. Fritsch, P. Friedlingstein, M. Glendining, C.A. Gracia, T. Hickler, J. House, M. Hulme, R.J.T. Klein, S. Lavorel, R. Leemans, M. Lindner, J. Liski, M.J. Metzger, J. Meyer, T. Mitchell, F. Mohren, P. Morales, J.M. Moreno, I. Reginster, P. Reidsma, M. Rounsevell, E. Pla, J. Pluimers, I.C. Prentice, A. Pussinen, A. Sánchez, S. Sabaté, D. Schröter,, S. Sitch, B. Smith, J. Smith, P. Smith, M.T. Sykes, K. Thonicke, W. Thuiller, G. Tuck, G. van der Werf, J. Vayreda, M. Wattenbach, D.W. Wilson, F.I. Woodward, S. Zaehle, B. Zierl, S. Zudin

A description of the entire assessment, its main results and conclusion can be found in the final project report (Schröter et al. 2004) which available at www.pik-potsdam.de/ateam/. Key publications concerning scenarios, ecosystem models (per sector), and the vulnerability concept are listed below.

Scenario development	
• Land use change scenarios	(Rounsevell et al. 2005 ; Ewert et al. 2005 ; Kankaanpäa & Carter 2004)
• Climate change scenarios	(Mitchell et al. 2004)

Agriculture	
• SUNDIAL	(Smith et al. 1996)
• ROTHC	(Coleman and Jenkinson 1996 ; Colemans et al. 1997)
Carbon storage	
• LPJ	(Stitch et al. 2003; Thonicke et al. 2001)
Biodiversity and Nature Conservation	
• statistical niche modelling	(Araújo et al. 2002 ; Thuiller 2003)
Water	
• Mac-pdm	(Arnell 1999; 2003)
Forestry	
• GOTILWA+	(Garcia et al. 1999 ; Sabaté et al. 2002)
• EFISCEN	(Nabuurs et al. 2000 ; Karjalainen et al. 2002)
Mountains	
• RHESsys	(Band et al. 1993, Tague and Band 2001,2004)

Vulnerability	
• Concept paper	(Metzger & Schröter 2005)
• Multi-scale methodology	(Metzger et al. 2005)
• ATEAM mapping tool	(Metzger et al. 2004)

Contents

Summary

The primary objective of the project ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling) was ro assess the vulnerability, with respect to global change, of human sectors relying on ecosystem functioning. A full suite of ecosystem models (covering biodiversity, agriculture, forestry, hydrology, and carbon sequestration) were run for the same internally consistent scenarios of alternative futures. Each model gives insights into the response of specific ecosystems, as in traditional impact assessments. Moreover, by integrating the results in a Vulnerability Assessment, more complex queries on ecosystems and ecosystem services for different regions can be answered as well. This report acts as a background document to the ATEAM Vulnerability Mapping Tool provided on the CD-rom. This software acts as a digital atlas of the many maps created by the ATEAM project, giving both the scientific community and other stakeholders access to the project's results. Besides generating fact sheets containing both maps and background information, the tool also includes some simple analysis functionality.

Chapter 1 gives a summary of the ATEAM project. ATEAM's primary objective was to assess the vulnerability of human sectors relying on ecosystem services with respect to global change. Multiple, internally consistent scenarios of potential impacts and vulnerabilities of the sectors agriculture, forestry, carbon storage, water, nature conservation and mountain tourism in the 21st century were developed for Europe. The full range of environmental impact scenarios, which are based upon IPCC's SRES narratives (Nakicenovic et al. 2000), provides spatially explicit projections of ecosystem services over time, including for the first time the variation across multiple plausible scenarios. This variation may be high. However, a considerable amount of it is due to the strongly differing socio-economic pathways in these scenarios. The set of multiple plausible global change scenarios showed severe changes in European climate and land use in the next century. The main trends in anticipated environmental impacts of global change seem clear enough to trigger both immediate action and further inquiry.

Chapter 2 provides a comprehensive manual to the ATEAM Mapping Tool. Maps are presented as fact sheets that not only show the map, but also hold information about the assumptions underlying the scenario, the modelling approach, and the uncertainties in the map. Besides the functionality of displaying fact sheets, the software also offers some analysis functionality that allows the user to zoom to specific regions, compare maps of different scenarios or time slices, perform simple queries, and summarise maps for multiple scenarios or time slices in scatter plots.

Chapter 3 discusses the scenarios used in ATEAM to provide alternative images of how the future might unfold for the modelled ecosystem services. Scenarios can act as an integration tool in the assessment of global change impacts in Europe. Because we cannot attatch any probability to any given scenario, they can help stimulate open discussion in the policy-arena about potential futures. To take full advantage of the scenario-approach, it is important to have an understanding of ways in which the data can be analysed and interpreted. Four guidelines are discussed that help in discussions about the results for the multiple scenarios.

Chapter 4 explains the ATEAM framework for assessing vulnerability. Vulnerability as assessed with the ATEAM approach is 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. A standardised index of the potential impacts was created to allow comparison of ecosystem services across the European environment. This index was combined with an indicator for society's adaptive capacity in order to create vulnerability maps for each ecosystem service.

Glossary

In the following we list and explain some of the more frequently used abbreviations for the convenience of the reader. Typically these abbreviations have been explained also on first appearance in the text.

A	adaptation
A1	see SRES
A2	see SRES
AC	Adaptive Capacity
ATEAM	Advanced terrestrial Ecosystem Analysis and Modelling The acronym of this project.
B1	see SRES
B2	see SRES
CGCM2	A global climate model used to estimate climate change resulting from greenhouse gas emissions
CSIRO2	A global climate model used to estimate climate change resulting from greenhouse gas emissions
E	Exposure to global change
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	A global climate model used to estimate climate change resulting from greenhouse gas emissions
IPCC	The Intergovernmental Panel on Climate Change
LPJ	The Lund-Potsdam-Jena Dynamic Global Vegetation Model.
NBE	Net Biome Exchange. The difference between net primary production and heterotrophic respiration.
NPP	Net Primary Production. The difference between gross primary production and autotrophic respiration.
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.
PA	Planned Adaptation
PCM	A general circulation model used to estimate climate change resulting from greenhouse gas emissions
PI	Potential Impact of global change
PIstr	stratitief potential impact to global change
RI	Residual Impact of global change
S	Sensitivity 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 Intergovernmental Panel on Climate Change
V	Vulnerability to global change

1. The ATEAM project[1]

Objectives

ATEAM (Advanced Terrestrial Ecosystem Assessment and Modelling) was a European Union 5th framework project that ran from January 2001 to June 2004. ATEAM's primary objective was to assess the vulnerability of human sectors relying on ecosystem services[2] with respect to global change. ATEAM considers vulnerability to be a function of potential impacts and the system's adaptive capacity to global change. Multiple, internally consistent scenarios of potential impacts and vulnerabilities of the sectors agriculture, forestry, carbon storage, water, nature conservation and mountain tourism in the 21st century were mapped for Europe with a spatial resolution of ca. 16 x 16 km for four time slices (1990, 2020, 2050, 2080).

Scientific achievements

Vulnerability as assessed with the ATEAM approach, is 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. We used a set of multiple, internally consistent socio-economic, climate, land use and nitrogen deposition scenarios, and developed a comprehensive modelling framework for projecting the dynamics of ecosystem services provided by European terrestrial ecosystems at a regional scale[3]. The ability of human sectors to implement planned adaptation measures is considered by introducing indicators of adaptive capacity. A strong dialogue with stakeholders was part of the assessment from the start of the project in order to provide applicable results to the management of natural resources in Europe.

We found that the provision of essential ecosystem services will change significantly with global change during the 21st century. Specific vulnerabilities of sectors and/or regions can be reduced by specific adaptation strategies:

- Land use change projections based on socio-economic and climatic changes project an overall decline in arable land in Europe. Climatic changes will shift crop suitability in agricultural regions. While the suitable area for some crops expands, some current agricultural areas become too hot and too dry to support agriculture for any crop type. To make use of the climate protection potential of biomass energy, shifts in suitable areas should be taken into account.

- In the forestry sector climate and land use changes are anticipated to have an overall positive effect on growing stocks in Northern Europe. However, negative effects were projected in other regions, such as drought and fire pose an increasing risk to Mediterranean forests. Management

---

1 This summary was taken from the final report of the ATEAM project (Schröter et al., 2004).

2 Ecosystem services are the conditions and processes through which ecosystems, and the organisms that make them up, sustain and fulfill human life (cf Daily, 1997).

3 The framework covers all 15 pre-enlargement EU countries, plus Norway and Switzerland at a resolution of 10'x10' (approximately 16x16km).

is paramount in the development of growing stock and forest productivity — intensive, sustainable forest management keeps the net annual increment at a high level.

- After an initial increase, the total terrestrial carbon sink strength (plants and soil) is projected to decline over time in Europe. In particular, the decrease in soil organic carbon is significant for all scenarios, calling for an increased attention to management practises that sustain soil fertility.

- In the water sector, climate change tends to increase the numbers of basins in southern Europe with water scarcity[4] and may produce simultaneously more severe droughts and more extreme floods in some areas of north-western Europe. Case studies for Rhine, Rhone and Danube indicate that changes in the timing of river flows, largely due to the reduction in the amount of snowfall, will affect both navigation and run-of-river hydropower potential. Hydropower plants might adapt their water storage strategies to prevent exceeded storage capacity at peak times.

- In the nature conservation sector accelerated extinctions indicate rapid biological impoverishment for most regions. This adverse trend for biodiversity could be mitigated by flexible management of nature reserve areas to maintain the conservation effect under changing environmental conditions.

- The mountain tourism sector will be impacted negatively in both winter and summer. In winter the elevation of reliable snow cover is expected to rise between 200 and 400 m, leaving many ski areas without sufficient snow. In summer the number of extreme heat days is likely to increase, thereby impacting on the attractiveness of mountain activities and increasing the number of mountaineering accidents.

- In comparison between European regions, the Mediterranean seems most vulnerable within Europe. Multiple potential impacts on multiple sectors were projected. These include water shortages especially in the summer months when demand peaks due to tourism, increased fire risk in the forestry sector, losses in the carbon storage potential, northward shifts in the distribution of tree species like maritime pine and cork oak, and losses of agricultural potential due to drought. In the Mediterranean these potential impacts combine with low adaptive capacity.

Socio-economic relevance and policy implications

This work contributes to the understanding of Europe's vulnerability to global change. Specifically, ATEAM assesses the rate and extent of climate and land use change, potential changes in ecosystem service supply and the vulnerability of key human sectors. Existing understanding of the dynamics of European ecosystems (managed and unmanaged) in the form of data and models, were assembled in a coherent framework. The ATEAM results facilitate sustainable environmental management and help evaluate the effectiveness of implementation measures such as the European Biodiversity Strategy. Project findings on Europe's carbon storage potential provide input to the debate around the Kyoto Protocol and support the design of climate protection strategies.

---

[4] *Water availability falls below 1000m^3 capita^{-1} year^{-1}.*

Stakeholder involvement

The project actively promoted the dialogue between stakeholders and scientists to increase mutual understanding and the usefulness of scientific results. The stakeholders included representatives of private land and forests, environmental resource managers, climate and environmental policy advisors, and scientists. The main communication took place during several workshops, in which methodology and results were discussed. By identifying their scientific information needs, stakeholders influenced the ecosystem service indicators that were modelled. Moreover, stakeholders were an important driving force behind the construction of the vulnerability mapping tool.

Main conclusions

The full range of environmental impact scenarios provides spatially explicit projections of ecosystem services over time, including the variation across multiple plausible scenarios. This variation may be high. However, a considerable amount of it is due to the socio-economic pathways. The set of multiple plausible global change scenarios showed severe changes in European climate and land use in the next century. Although some of the expected impacts may be considered positive (e.g. increases in forest area and productivity), and others hold potential opportunities for the future (e.g. "surplus land" for extensification of agriculture), most of the anticipated changes have negative impacts on ecosystem service supply, and therefore human society (e.g. declining soil fertility, increased fire risk, biodiversity losses). The main trends in anticipated environmental impacts of global change seem clear enough to trigger both immediate action and further inquiry.

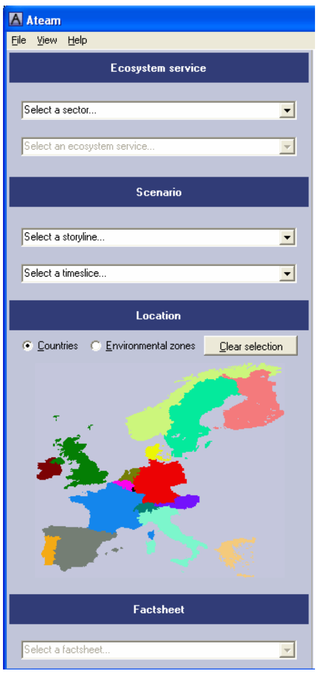
2. The Vulnerability Mapping Tool

Introduction

The ATEAM project has produced a wealth of spatial information. There are scenarios for climate and land use change, with maps for baseline conditions and 7 scenarios, each characterised by 3 time slices (1990-2020; 2020-2050 and 2050-2080). Then there are the maps of ecosystem services that were modelled for all these scenarios. Finally there are maps related to the vulnerability assessment. At an early stage it became clear that in order to communicate the results of ATEAM, both to stakeholders and the scientific community, some form of digital atlas would be required. The Vulnerability Mapping Tool now includes a database of more than 1200 maps. These maps are presented as fact sheets that not only show the map, but also hold information about the assumptions underlying the scenario, the modelling approach, and the uncertainties in the map. Besides the functionality of displaying fact sheets, the software also allows for some simple analysis of the underlying data: a user can zoom in on specific regions, compare maps of different scenarios or time slices, perform simple queries, and summarise maps for multiple scenarios or time slices in scatter plots. This chapter acts as a comprehensive manual to the mapping tool. The methodology used to create vulnerability maps, and definitions of related terms, are explaine din detail in Chapter 4.

Creating fact sheets

The ATEAM Vulnerability Mapping Tool presents maps as fact sheets which contain a map, as well as summarised background information to help interpret the map. To create a fact sheet for an ecosystem service indicator, you need to select several specifiers from the column on the left side of the screen (Fig. 1):



1.	select a sector	(e.g. agriculture)
2.	select an ecosystem service indicator	(e.g. farmer livelihood)
3.	select a scenario	(e.g. B1)
4.	select a time slice	(e.g. 2050-2080)
5.	select the type of fact sheet	(e.g. vulnerability)

Figure 1. Menu where specifiers for the fact sheet are selected.

After selecting the specifiers a fact sheet is generated in the right panel of the screen (Fig. 2).

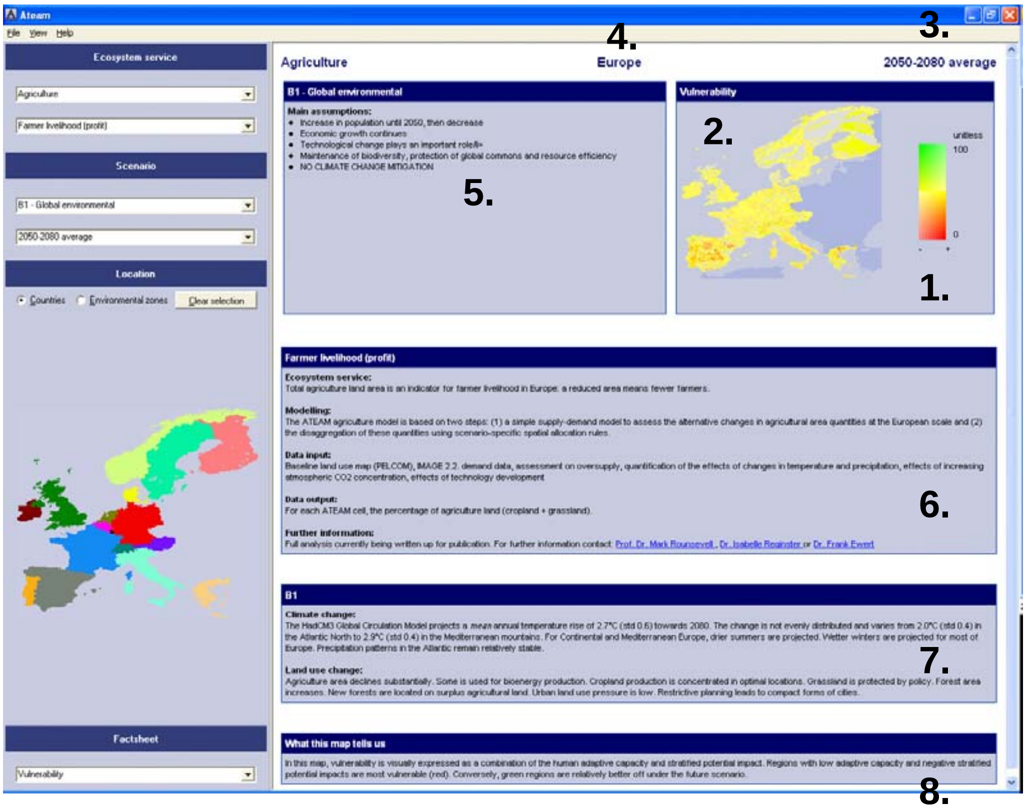


Figure 2. Fact sheet for the ecosystem service *Farmer livelihood* for the B1 scenario and the 2050-2080 time slice. The fact sheet gives information about: the map and legend (1); the type of map (2); the time slice (3); the spatial extent of the map (4); the scenario and main assumptions (5); the mapped theme (6); the climate and land use scenario (7); what the map shows (8).

Besides making fact sheets for maps related to ecosystem services, it is possible to make similar fact sheets for maps related to the global change exposures. These are the maps of the land use and climate change scenarios as well as some maps of the socio-economic assumptions used to create the land use maps. In the menu-bar, under <<View>> and <<Map>> you can choose between <<Ecosystem Service>> and <<Exposure>>. By selecting <<Exposure>>, the qualifier drop-down menus are adjusted for Exposures. In a similar manner as before, it is now possible to make fact sheets for future Climate, Land use, and socio-economic exposures.

Fact sheets can be printed and exported as .pdf files. Both options are located under <<File>> in the menu-bar.

Analysing maps

Zooming in to selected region

By clicking on the map in the column with the specifiers it is possible to zoom-in to individual countries, or Environmental Zones. This functionality helps in analysing differences within and between regions. Fig. 3 shows that in most of Italy there is an increase in bird biodiversity, except for the Po Valley, where this scenario shows a decrease.

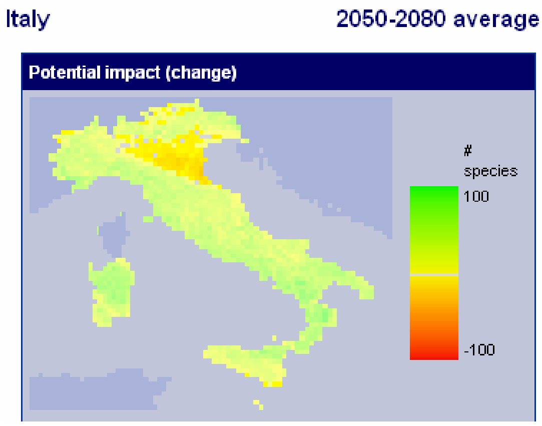


Figure 3. Change in number of bird species in Italy for the A2 scenario.

Comparing scenarios or time slices

In the scenario drop-down menus it is possible to select the options <<all storylines>> and <<all time slices>>. When one or both of these options is selected a fact sheet is created with multiple maps. These fact sheets give a quick overview of the development over time and the differences between the scenarios (Fig. 4).

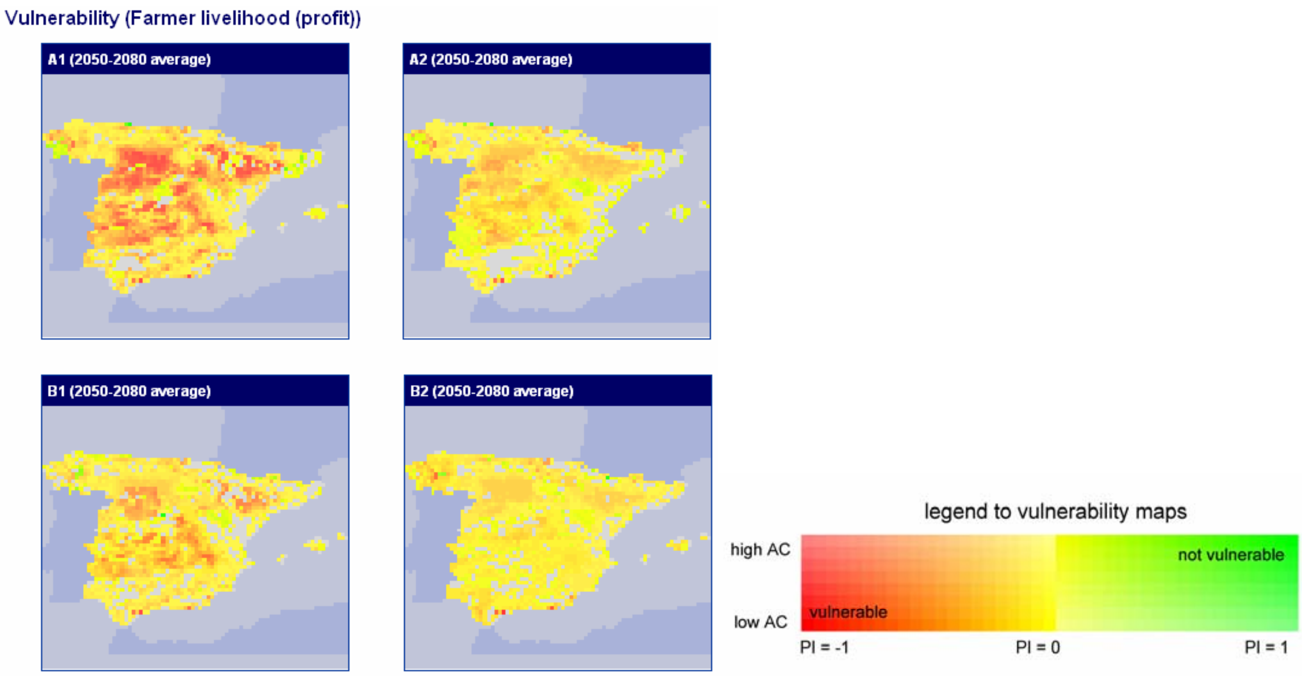


Figure 4. Displaying multiple maps helps in analysing or comparing effects of different scenarios. The vulnerability methodology is explained in Chapter 4.

Simple map queries

Under <<View>>, <<Map>>, <<Map query>> you find a simple tool that allows you to identify regions with values above and below a selected cut-off value. Fig. 5 gives an example of such an analysis for regions with mean maximum spring temperature > 15°C. Also, in this window you can determine the exact values within the map by moving the cursor over it. The value for the location of the cursor is given at the bottom of the map. The right map provides all regions above (or below) the cut-off value. In Fig. 5 the mean maximum spring temperature in Wageningen is 15°C.

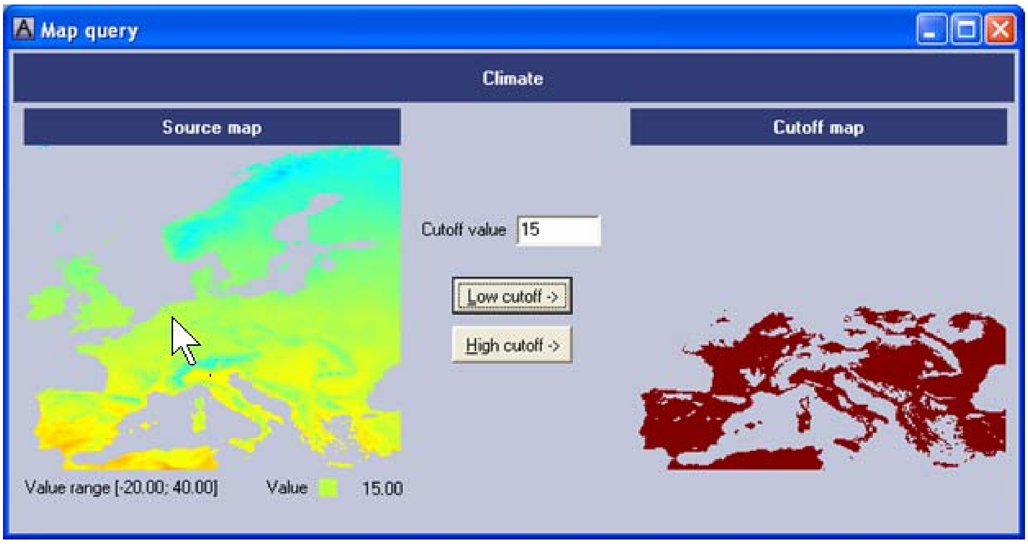


Figure 5. Example of a simple map query that can be preformed with the mapping tool (see text).

Using scatter plots to compare results

The most advanced analysis option in the software is the possibility to make scatter plots that summarise multiple maps. You can make two types of scatter plots: (1) plots for different regions for one time slice (Fig 6), or (2) plots for different time slices for one region (Fig. 7).

Under <<View>>, <<Comparison>> you can select whether you want to compare ecosystem service or exposure maps. Similar to creating fact sheets, you first need to select specifiers in the left-hand column. You also need to select whether you want to make a plot for one time slice (and multiple regions) or for one region (and multiple time slices). When enough specifiers have been selected the <<Do compare>> button can be clicked in order to produce a scatter plot.

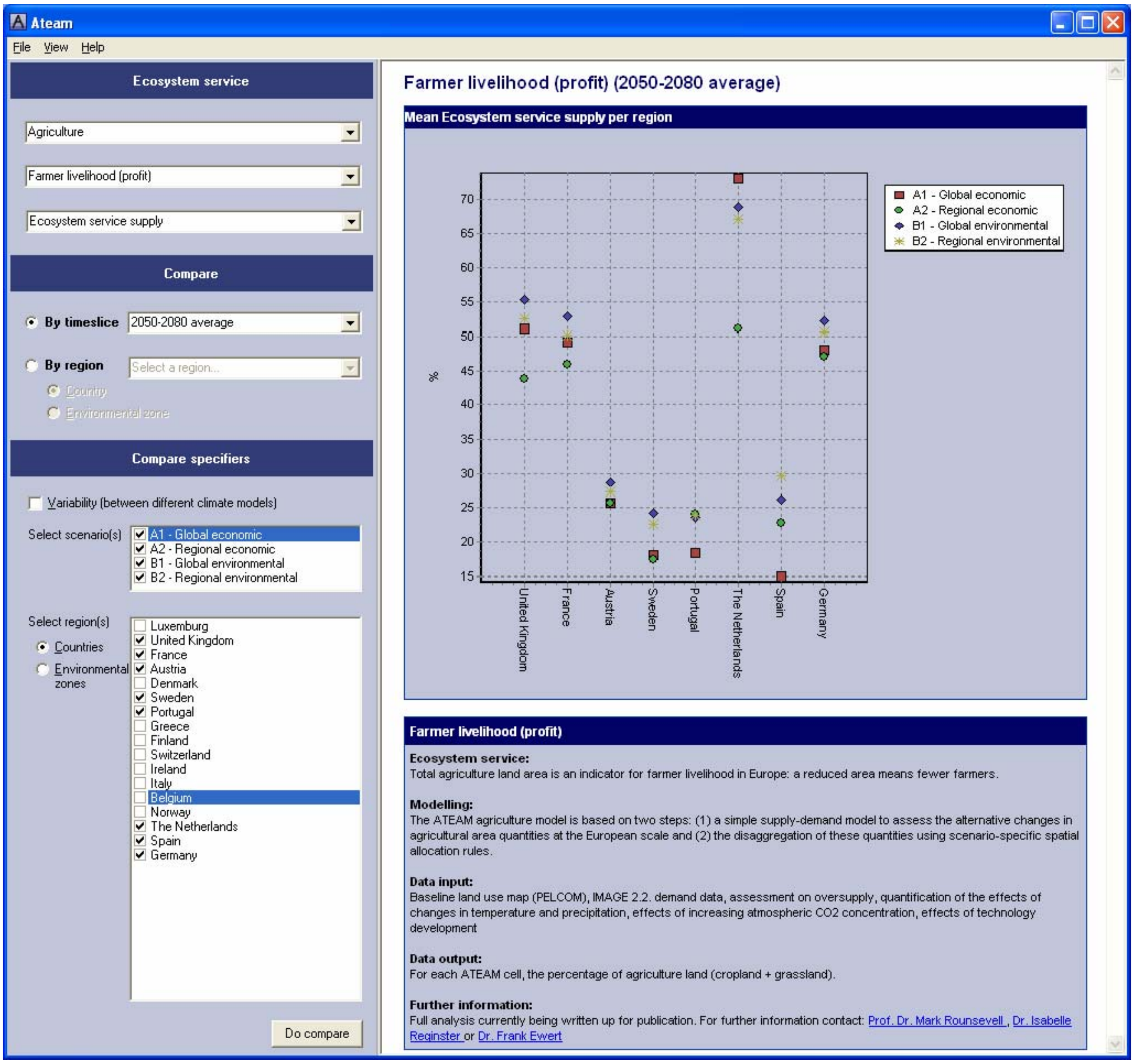


Figure 6. Scatter plot for the ecosystem service *Farmer livelihood* for the 2050-2080 time slice. There are large differences between countries, both in the values of the ecosystem services, and in the impacts of the scenarios. For instance, in most countries, the A1 – global economic scenario results in the lowest farmer livelihood, except in The Netherlands where the A1 scenario leads to the highest farmer livelihood value.

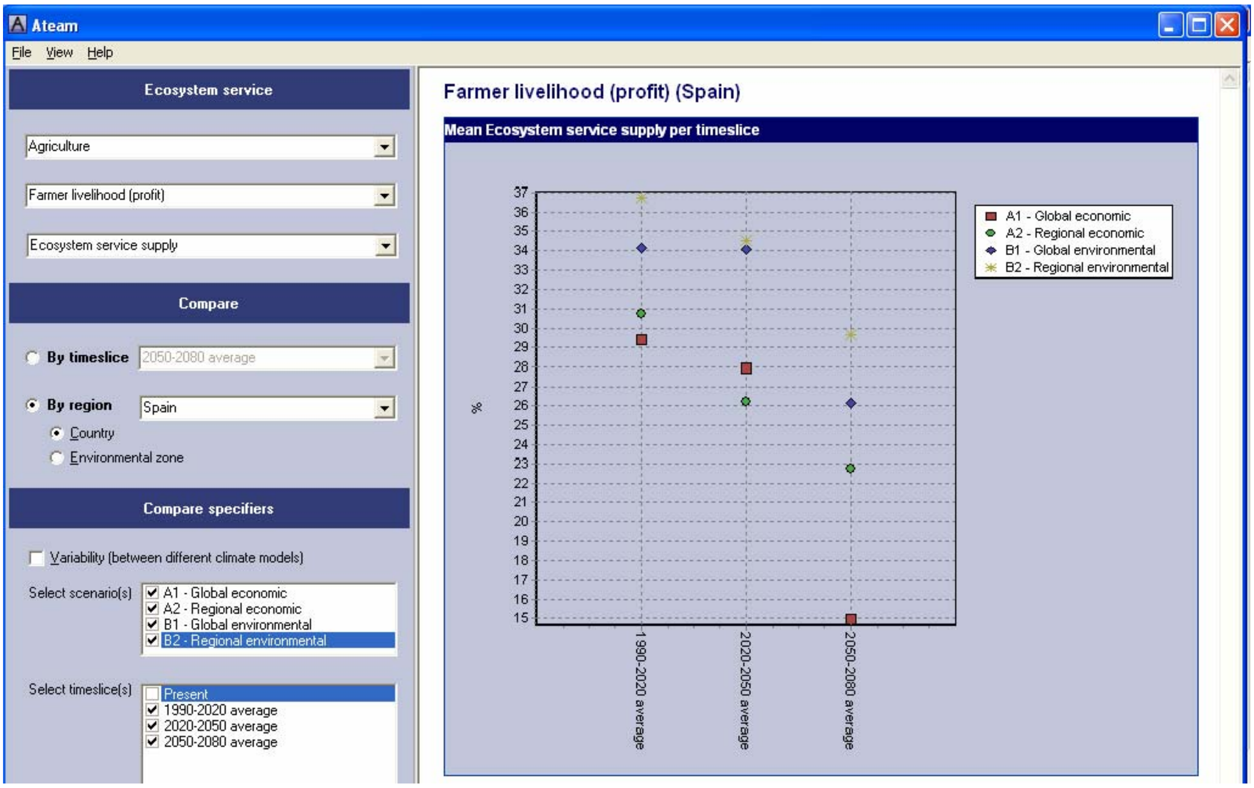


Figure 7. Scatter plot for the ecosystem service indicator “farmer livelihood” in Spain for three future time slices. The present value is 38% (not shown). This plot shows how the ecosystem service decreases during the 21st Century. Comparison shows that there are large differences in the potential impact of the different scenarios.

Variability between Global Climate Models

One important aspect to keep in mind when analysing potential impacts of global change scenarios is the uncertainty in the climate change projections. While there is general agreement between Global Climate Models (GCMs) in the trends of temperatures change, the extent of the change differs between GCMs. In ATEAM, all scenarios were run with the Hadley Centre Climate Model 3 (HadCM3). The most cases the A2 scenario was also modelled for three other GCMs, called CSIRO2, CGCM2 and PCM. In comparison, HadCM3 predicts the greatest changes, and PCM is the most modest. Change in precipitation shows greater variability as well as disagreement in regional trends. Annex 1 gives an overview of the variability in the ATEAM climate and land use scenarios for the different Environmental Zones. When analysing the ecosystem service indicators in the mapping tool, it is very important to also analyse the influence of the variability in climate projections on the model results (see also Chapter 3). This can be done by marking the box <<Variability between different climate models>> in the scatter plot interface. A scatter plot is generated for the A2 scenario for up to 4 GCMs, so that the variability between GCMs becomes apparent.

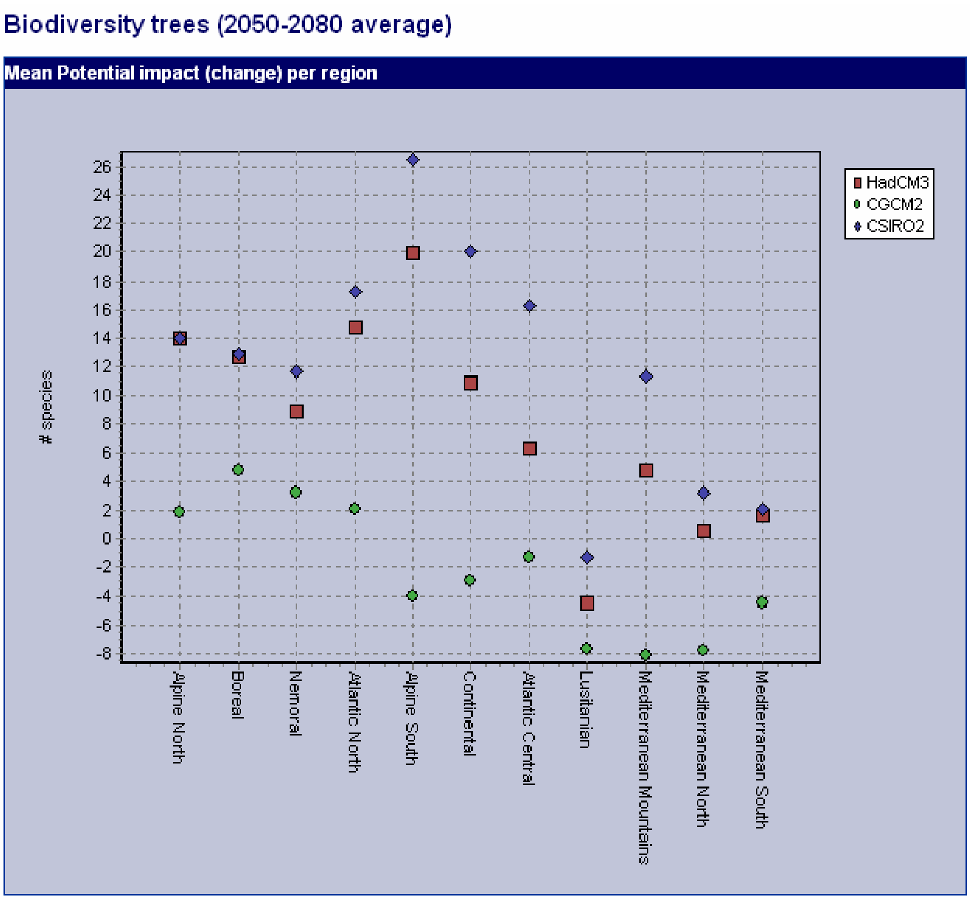


Figure 8. Scatter plot of the mean change in tree biodiversity in 2080 compared to the current situation for the different Environmental Zones, under the A2 scenario for three different GCMs. The variability between the different GCMs is large. For example, in the most extreme case, the Alpine South, the results range from a mean decrease of 4 species to an increase of 27 species.

3. Interpreting scenarios and potential impacts

Introduction

Scenarios are alternative pathways of how the future might unfold and are nowadays widely used in assessing the medium and long-term consequences of ongoing global environmental change. They are not predictions, to which likelihood can be attached. Rather they describe plausible futures as a function of changes in major driving forces, such as demographic changes, economic development or technological change.

When considering the large temporal and spatial scales of global environmental change, scenarios provide an effective means to organise and structure an enormous amount of observational information, model results and personal insights. Scenarios illustrate future developments (for example, in technology or agriculture) in both qualitative and quantitative terms. They are a way to assess the future, and, in doing so, they provide an opportunity to anticipate undesirable trends and to devise effective responses by modifying current policies and decision-making.

The ATEAM scenarios

The main socio-economic drivers of environmental change are global in scope and are inherently unpredictable. Given such uncertainties, future environmental conditions can only roughly be approximated at regional and local scales. Therefore, in order to represent this uncertainty, comprehensive global narratives or storylines were developed for the IPCC Special Report on Emission Scenarios (SRES) (Nakicenovic et al. 2000). These depict qualitatively different future directions in a world without explicit climate change policies. They also provide quantitative estimates (using integrated assessment models) of greenhouse gas and aerosol emissions from energy use, industrial activities and land use. The likely responses of the atmosphere to these emission estimates are described in the IPCC Third Assessment Report (TAR).

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 emphasises a largely different set of social and economic ideals. These ideals are organised along two axes. The vertical axis represents a distinction between more economically (A) and more environmentally and equity (B) oriented futures. The horizontal axis represents the range between more globalisation (1) and more regionally ortiented developments (2). To illustrate differences in emissions due to different combinations of energy carriers (e.g. fossil versus renewable), the A1 scenario was split into 3 different ones (fi: fossil intensive; b: a mixed set and t: only renewables). For our analysis we have only used A1fi, which resulted in the highest emissions.

To obtain climate projections, different Global Climate Models (GCMs) have been run for the scenarios and the results are available through the IPCC data distribution centre. For ATEAM, climate change scenarios from four state-of-the-art GCMs (HadCM3, CSRIO2, CGCM2 and PCM) were downscaled to a 10’x10’ resolution (Mitchell et al. 2004). The scenarios were anomalised relative to the observed climatology from 1961-90 to produce information about future European climates at a spatial resolution that would not have been possible using models alone. Between the different GCMs there is general agreement in the trends of temperatures change. In comparison, HadCM3 predicts the greatest changes, and PCM is the most modest. Change in precipitation shows greater variability as well as disagreement in regional trends. Annex 1 gives an overview of the variability in the ATEAM climate and land use scenarios for the different Environmental Zones. The 16 alternative future climates (4 scenarios x 4 GCMs) represent (at the global scale) 93% of the range of possible global warming presented by the IPCC.

The scenarios of socio-economic and land use change (Rounsevell et al. 2005; Ewert et al. 2005; Kankapaanpäa & Carter 2004ab), are based on the same IPCC SRES marker scenarios and take into account the climate projections described in the previous paragraph. The global socio-economic drivers of the SRES scenarios were downscaled to the European and regional scale. Changes in agricultural land use were calculated from food supply-demand relationships considering effects on food production of climate change, increasing CO_2 concentration, and technological development. Data on land areas required to meet the demand for food, biomass energy crops, forest products and urban areas were derived from the IMAGE model (IMAGE team 2001). Allocation of land use changes were based on scenario-specific assumptions about policy regulations. A hierarchy of importance of different land use types was introduced to account for competition between land use types and to assign the relative coverage of 14 main land use types to each 10’x10’ grid cell (Rounsevell et al. 2005). Experts as well as stakeholders from various sectors were involved in the development of the land use scenarios. A set of seven land use scenarios that are linked to the climate projections are available (A1, A2, B1, B2 driven by climate from HadCM3, and A2 additionally driven by climate from CSRIO2, CGCM2 and PCM). Fig. 9 gives a summary of the main impacts of the land use change scenarios.

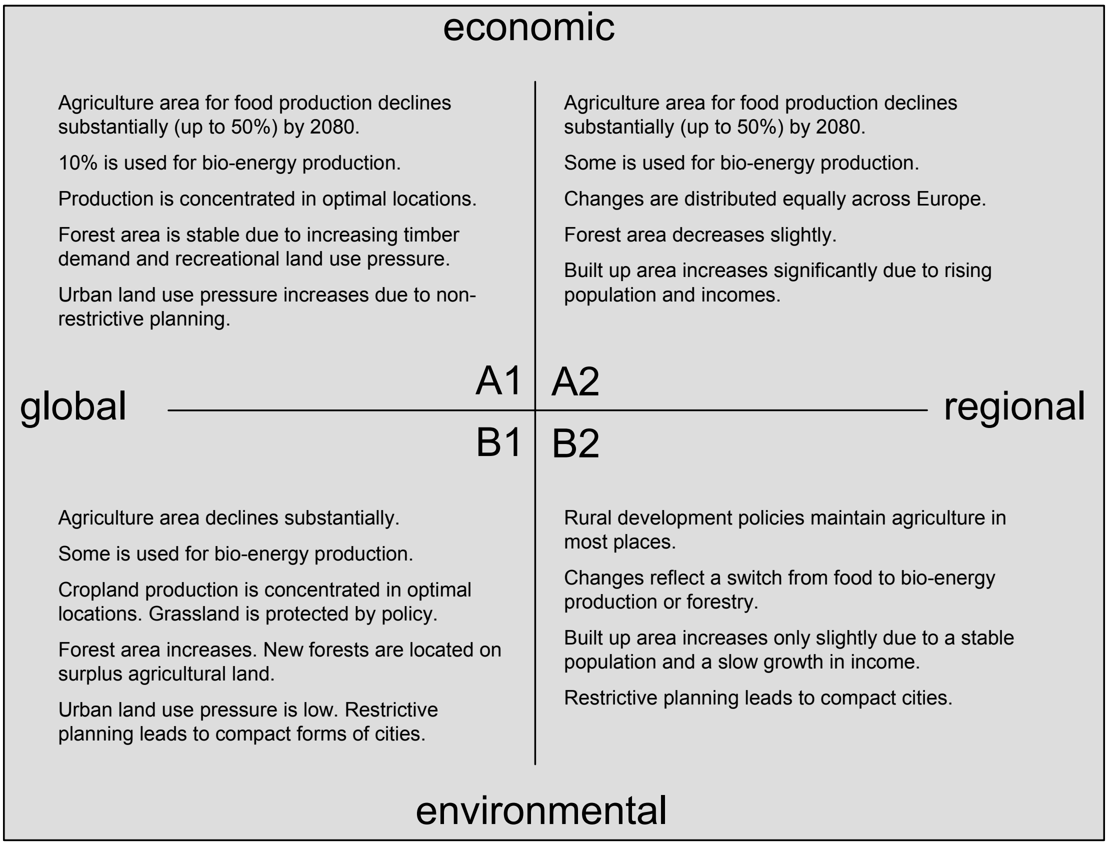


Figure 9. Summary of the main trends in the ATEAM land use change scenarios (Rounsevell et al. 2005).

Guidelines for interpretation

The ATEAM scenarios, and the ecosystem services that were modelled for the scenarios, provide alternative images of how the future might unfold and can act as an integration tool in the assessment of global change impacts in Europe. Because we cannot attach probability to any given scenario, they can help stimulate open discussion in the policy-arena about potential futures. To take full advantage of the scenario-approach it is important to have an understanding of ways in which the data can be analysed and interpreted. In this section four important guidelines are discussed that help in the discussion about the results for the multiple scenarios. These guidelines are:

> **1. Be aware of the major sources of uncertainty**
> **2. Examine the spatial differences in potential impacts**
> **3. Examine the relative position of different scenarios**
> **4. Examine the variability between the scenarios**

Uncertainties in future projection (1)
In order to interpret the model outputs for the different scenarios it is important to have an understanding of most important sources uncertainty. There are four major sources:

Uncertainties in the SRES scenarios. – The four SRES marker scenarios used in ATEAM cover 93% of the range of possible global warming presented by IPCC (Nakicenovic et al. 2000). It is however important to realise that all scenarios are essentially arbitrary and therefore do not likely depict the most realistic future.

Uncertainties in global mean climate sensitivity and in regional patterns of climate change. – While there is general agreement between GCMs in trends in temperature change, change in precipitation shows greater variability as well as disagreement in regional trends (see Annex 1). This variability between GCMs reflects both the limitation to model the finer scale spatial and temporal processes involved in the generation of precipitation in all its different forms (e.g. snow, drizzling rains, and heavy showers) of our current understanding of the climate systems. This is one of the major sources of uncertainty for future climate projections. This variability directly influences the uncertainty of results generated by ecosystem models that rely on such climate projections. Within the Mapping Tool it is possible to detect this cause of uncertainty by making scatter plots that show the variability in the A2 scenario for climate variables from 4 GCMs (see pg. 23). When the variability caused by the different GCMs is greater than the variability caused by the emission scenarios, it is difficult to be confident about analyses based on the climate scenarios.

Uncertainties in land use projections. – It is impossible to validate scenarios in the classical sense, because there are no observations for the future. A partial validation of the supply/demand model was preformed successfully using historic agricultural statistics (Rounsevell et al. 2005). However, the land use scenarios depend heavily on the interpretation of the SRES assumptions, especially those on technological development (Rounsevell et al. 2005). As stated above, it is important to realise that all scenarios are essentially arbitrary and therefore highly uncertain.

Uncertainties in ecosystem models. – There are uncertainties associated with the different modelling techniques and models for ecosystems and ecosystem services. Some uncertainties are reported in the fact sheets that are produced by the Mapping Tool. Specific details of model uncertainties are reported in the model documentation. Thuiller (2004) has carried out a detailed study about the influence of model selection, showing that of all uncertainties the selected modelling technique causes the greatest variability in determining species' range shifts under climate change.

Spatial differences in the impacts (2)

Global changes will not be uniformly distributed across Europe. Both climate and land use changes will have different effects in different regions. Annex 1 gives a summary of the ATEAM scenarios for different Environmental Zones (EnZ) in Europe, and illustrates how both climate and land use projections are different between these zones. For instance, Alpine North and Boreal zones face an increase in precipitation, while the Mediterranean zones become dryer. The Mediterranean is also the region where the decrease in agricultural land is most dramatic. These differences in exposures influence the modelled change for the ecosystem services. As Fig. 10 illustrates, there is an increase in wood production in all EnZs, but the extent of this increase differs greatly between regions.

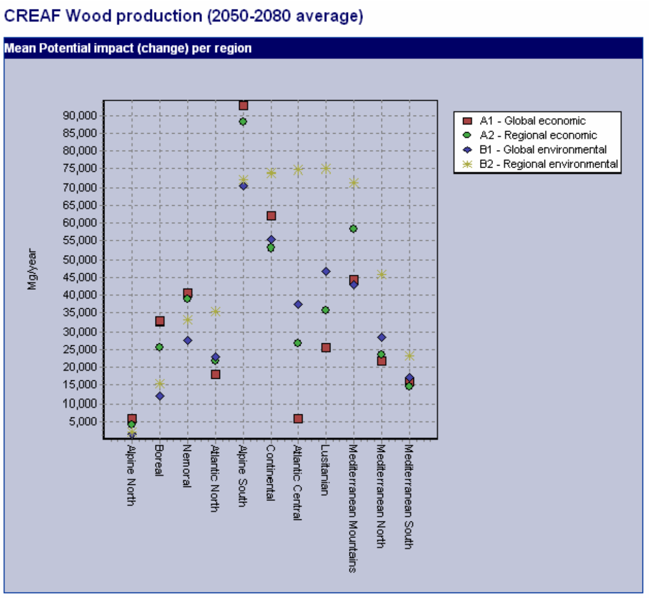


Figure 10. Mean change in wood production between 2080 and present, summarised per Environmental Zone for the different scenarios.

Relative position of different scenarios (3)

The range of the modelled ecosystem services for the different scenarios does not represent the likelihood of occurrence, but does provide an important context for understanding the relative position of a scenario. For example, in Fig. 10, the A1 (global economic) scenario results in the greatest increase in wood supply in the Alpine North, Boreal, Nemoral, and Alpine South. In The Mediterranean region the A1 scenario is less favourable. In fact, the opposite B2 (regional environmental) scenario is the most favourable scenario for these regions. It is important to look closely at the relative position of the scenarios in a region to anticipate the effect of alternative policy options or development pathways.

Variability between scenarios (4)

While the variability between the modelled ecosystem service indicators for the different scenarios cannot be used to assign probabilities, they can be used to see whether changes in a region differ under alternative development pathways. For instance, Fig. 10 shows that in the Atlantic North there are only small differences between the different scenarios, whereas the differences in Atlantic Central span a wide range. Policy options are therefore more likely to influence wood production in Atlantic Central than in Atlantic North.

4. The ATEAM vulnerability framework[5]

Introduction

Even if human society is very successful in entering a sustainable development pathway, significant global changes are likely to occur within this century. The atmospheric carbon dioxide concentration could double compared to pre industrial concentrations, while the global average surface temperature is projected to increase by 1.4-5.8°C by 2100 (IPCC 2001a). Land use changes will have an immediate and strong effect on agriculture, forestry, rural communities, biodiversity and amenities such as traditional landscapes (UNEP 2002; Watson et al. 2000). In the face of these changes, the question posed by Kates and colleagues (2001) of '*How to integrate or extend today's operational systems for monitoring and reporting on environmental and social conditions to provide more useful guidance for efforts to navigate a transition towards sustainability?*' obtains new urgency. Vulnerability assessments aim to inform the decision-making of specific stakeholders about options for responding and adapting to the effects of global change (Schröter et al. 2004). The large potential, but still early stage of development, of spatially referenced modelling and GIS mapping methods for vulnerability assessment has been recognised (Kasperson et al. 2001). This paper describes an approach based on such spatially explicit methods developed to assess where in Europe people may be vulnerable to the loss of particular ecosystem services, associated with the combined effects of both climate and land use change.

Ecosystem services form a vital link between ecosystems and society through providing food and timber, clean water, species conservation, aesthetic values and many other necessities. Impacts of global changes on ecosystems have already been observed (see reviews by Smith et al. 1999, Sala et al. 2000, Stenseth et al. 2002, Walther et al. 2002, Parmesan and Yohe 2003, Root et al. 2003; Leemans and Van Vliet, 2004). Such impacts are of direct importance to human society, because ecosystems and the organisms that make them up provide services that sustain and fulfil human life (Daily 1997; Millennium Assessment 2003). Therefore, in addition to immediate global change effects on humans (e.g. environmental hazards), an important part of our vulnerability to global change results from impacts on ecosystems and the services they provide.

In the vulnerability approach used for this European assessment, the provision of ecosystem services is used as an approximate measure of human well-being adversely impacted by global change stressors, similar to the approach suggested by Luers et al. (2003). These measures are indicators of ecosystem services that were selected in a close consultation process with stakeholders from sectors relying on these ecosystem services. Different ecosystem modelling techniques are used for different sectors, but all ecosystem models use the same set of internally consistent input scenarios for climate change and land-use change.

The Synthesis chapter of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR) Working Group II (Smith et al 2001) recognized the limitations of static impact assessments and put forward the challenge to move to dynamic assessments that are a function of shifting climatic parameters, trends such as economic and population growth, and the ability to innovate and adapt to changes (IPCC 2001b). A step towards meeting this challenge is the emergence of a common definition of the term "vulnerability":

---

5 *This chapter is based on a manuscript submitted to Regional Environemntal Change (Metzger & Schröter, 2005).*

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 2001b).

The vulnerability concept introduced here (see next section) is based on this definition and was developed to integrate results from a broad range of different, spatially explicit models. Projections of changing ecosystem service provision and changing adaptive capacity are integrated into spatially explicit maps of vulnerability for different human sectors. Such vulnerability maps provide a means for making comparisons between ecosystem services, sectors, scenarios and regions to tackle multidisciplinary 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 is defined in such a way that it includes both the traditional elements of an impact assessment (i.e. sensitivities of a system to exposures), and adaptive capacity to cope with potential impacts of global change (Schröter et al. 2004; Turner et al. 2003). To ensure the relevance of the vulnerability maps, stakeholders were consulted at specific points throughout the project.

The following sections describe the concept for a spatially explicit and quantitative vulnerability assessment for Europe. We give an overview of the different tools used to quantify the elements of vulnerability, and of how we integrate these elements into maps of vulnerability. The approach is illustrated by an example from the carbon storage sector, using climate protection as an ecosystem service that human society has become aware of in recent years.

The vulnerability approach

Towards a quantification of vulnerability

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 of vulnerability. However, because vulnerability assessments consider not only climate change, but also other possible stressors such as land use change (Turner et al. 2003), some of the IPCC definitions were modified somewhat. Furthermore, we adjusted the definition of vulnerability so that it is more directly related to the human-environment system[6]. In this paper we assess the vulnerability of human sectors, relying on ecosystem services:

Vulnerability is 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.

Table 1 lists the definitions of fundamental terms used in this paper and gives an example of how these terms could relate to the carbon storage 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

---

6 We talk about the 'human-environment system' to acknowledge the fact that humans, as users, actors and managers of the system are not external, but integral elements of the studied unit. The term reflects the importance of the system's social, ecological and economic features alike. Various other terms have been coined to name such systems, e.g. 'nature-society system' (Kates et al. 2001), 'eco-social system' (Waltner-Toews 2003), 'linked social-ecological system' (Walker et al. 2002); and processes in such systems have been called 'civilisation-nature-interactions' (Petschel-Held et al. 1999).

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 just 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

Table 1. Definitions of important terminology related to vulnerability, with an example for the carbon storage sector. IPCC TAR = Intergovernmental Panel on Climate Change Third Assessment Report (IPCC 2001c).

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	Increased demand, increased fire risk
Sensitivity	**(S)**	The degree to which a human-environment system is affected, either adversely or beneficially, by environmental change.	Ecosystem Models	Ecosystems that store carbon are affected by environmental change
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.		Increase in storage
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.

These simple conceptual functions describe how the different elements of vulnerability are related to each other. Nevertheless, they are not operational for converting model results into vulnerability maps. Operationalising these functions requires various tools and several steps, which we describe in detail below. An overview of the steps involved in the vulnerability assessment is depicted in Figure 1. Using global change scenarios as input data, ecosystem services and a generic adaptive capacity index are modelled spatially for three time slices and baseline conditions (ecosystem services at 10’x10’ resolution; adaptive capacity index at province level). The indicators are then combined to produce vulnerability maps.

This vulnerability framework facilitates integrated analyses and comparisons between the multitude of maps of ecosystem services, and between sectors, scenarios, regions and points in time (time slices). Several examples of possible questions that a vulnerability framework could help answer were listed in the introduction. The framework is designed to produce maps that are intuitive to users outside the scientific community. In the next section, the vulnerability framework is explained by an example.

Creating a vulnerability map– an example

In this chapter we focus on the ecosystem service climate protection, and its indicator carbon storage (net biome exchange) as an example to present the ATEAM methodology for mapping and analysing vulnerability. With the goal of reducing greenhouse gas (GHG) emissions, the Kyoto protocol creates two mechanisms, GHG emissions trading and the Clean Development Mechanism (CDM). Important CDM strategies are carbon dioxide emission reduction by using hydropower and biomass energy, as well as by maintaining important carbon sinks like soil organic matter and European forests. Within this political framework, climate protection through net terrestrial carbon storage becomes an obvious ecosystem service. Therefore information on actual and potential European carbon storage is useful to politicians in negotiations regarding the Kyoto process.

Throughout the project we collaborated with stakeholders interested in carbon storage, which included representatives of national and European forest owners, land owners, agricultural producers, paper industry, consultancy groups to the paper industry, farm management agencies, consultancy groups to environmental engineers, environmental finance companies, national and European representatives of environmental agencies, as well as biomass energy companies and foundations. These stakeholders expressed an interest in the carbon storage potential of their land and the carbon budget of the use of biomass energy crops and biomass side products, such as straw from wheat production. Depending on European Union (EU) mitigation policies, these stakeholders may receive credits for carbon storage. Besides estimating carbon storage in Europe’s terrestrial ecosystems we therefore also considered the carbon offset of biomass energy crops (including the carbon/energy balance for crop production, transport and energy conversion processes). However, the example given in this paper refers to regional carbon storage in plants and soils only, not to substitution of fossil fuels with biomass energy crops. Besides the direct commercial interest in carbon storage, stakeholders also mentioned the potential positive side effects of increasing the carbon storage in terrestrial biomass, such as enhanced recreational value of a landscape and possible positive impacts on water purification.

The following sections elaborate on, and quantify, the elements of the vulnerability functions for net carbon storage under one scenario and one Global Climate Model (GCM), resulting in vulnerability maps for people interested in climate protection.

Exposure
For global change research, the IPCC recommends to use a family of future scenarios that captures the range of uncertainties associated with driving forces and emissions, without assigning probabilities or likelihood to any individual scenario (Carter et al. 2001). Our study is therefore based on multiple quantitative scenarios of global change, which are derived from the A1fi, A2, B1 and B2 scenarios developed for the IPCC Special Report of Emission Scenarios (SRES) (Nakicenovic et al. 2000). In summary, exposure in our study is represented by a consistent set of spatially explicit scenarios (10'x10' resolution for the 15 European Union countries plus Norway and Switzerland) of the main global change drivers, i.e. socio-economic variables, atmospheric carbon dioxide concentration, climate, and land use for three time slices (2020, 2050, 2080) and baseline conditions (1990). The scenarios have been discussed in more detail in Chapter 3.

Ecosystem service provision and Potential Impact
In our study we assess potential impacts (PIs) of global change on ecosystems as a function of sensitivity and exposure (see equation 2 above). Potential impacts are manifested in changes in ecosystem service supply. The indicators of ecosystem services are used as measures of human well-being, similar to the approach introduced by Luers et al. (2003). Our ecosystem models represent subsystems within the human-environment system, such as agricultural land, managed forests and catchments, and managed nature reserves. Under a certain exposure, determined by a scenario, ecosystem models calculate maps of ecosystem services as they are 'provided' by the human-environment subsystem. The potential impact of a particular scenario can be determined by calculating the change between a future time slice and baseline conditions.

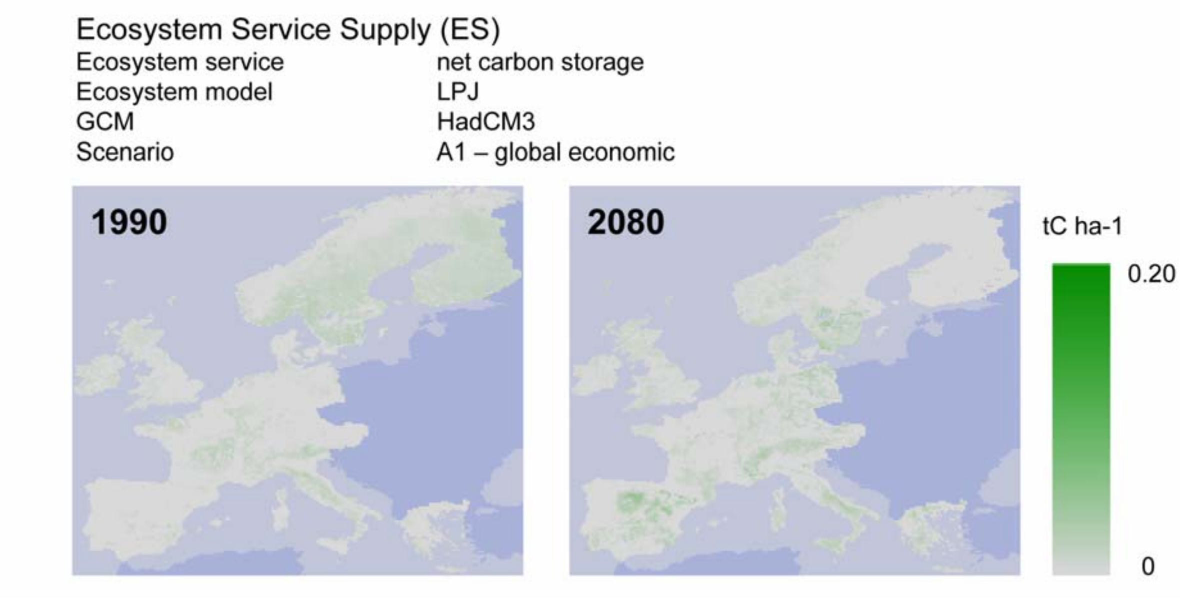


Figure 11. Net carbon storage across Europe as modelled by the LPJ model for the A2 scenario and the HadCM3 GCM for climate and land use change. Grey areas are net sources of carbon. Carbon emission is not mapped here because in the vulnerability framework introduced here, ecosystem services and antagonist disservices cannot me mapped together.

Figure 11 shows the results of the first step towards mapping potential impacts on the carbon sector – the ecosystem service carbon storage under a specific climate and land use scenario (A2 – regional economic, HadCM3 GCM). The ecosystem service carbon storage is indicated by the variable net biome exchange (NBE), which is provided by the dynamic global vegetation model LPJ (Sitch et al. 2003). The NBE of an area is determined by net primary production (NPP, net carbon uptake by the plants), and carbon losses due to soil heterotrophic respiration, fire, harvesting, and land use change. Net carbon storage is the integral of NBE (sources plus sinks) over time. Net carbon uptake (positive NBE) is valued as an ecosystem service to reduce carbon dioxide concentrations in the atmosphere. Net carbon emission (negative NBE) is regarded as an ecosystem disservice, adding to the atmospheric carbon dioxide concentration. The amounts of carbon that can be efficiently stored in terrestrial vegetation over long periods of time need to be considered in terms of absolute numbers, in relation to other pools and fluxes (atmospheric concentration, anthropogenic emissions, uptake by the oceans) and within the political context.

Stratified ecosystem service provision and the stratified potential impact index

Maps of potential impact, defined in the previous section as the change in ecosystem service provision compared to baseline conditions, are valuable for analysing impacts in a certain region. However, because ecosystem services tend to be highly correlated with environmental factors, they do not allow for comparisons across the European environment. Inherently, 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 have a far lower biodiversity (1477 vascular plant species (van der Meijden et al. 1996)), but a very 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 grain yield levels are less useful measures for comparing regional impacts between these countries. A relative change 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. Table 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 also be interpreted with great care and cannot easily be compared.

Table 2. Example of changing ecosystem service supply (e.g. grain yield in t ha-1 a-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 id 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
Ecosyem 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 (ES str)	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**

For a meaningful comparison of grid cells across Europe it is necessary to place values of ecosystem service provision 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 ecosystem services (Metzger et al. in press).

The EnS was created by statistical clustering of selected climatic and topographic variables into 84 strata and 13 aggregated Environmental Zones (EnZ) (Metzger et al. in press), as summarized in Annex II. The aggregation into EnZs is based on cut-off levels in the mean first principal component score of the clustering variables for each stratum. The EnS was constructed using tried-and-tested statistical procedures and shows significant correlations with principal European ecological datasets. Furthermore, a comparison between the EnS and other European classifications, using the Kappa statistic (Monserud & Leemans, 1992), indicate 'good' or 'very good' agreement (Metzger et al. in press). For each stratum a discriminant function was calculated for the variables available from the climate change scenarios described above (section Exposure and Chapter 3). With these functions the 84 climate strata were mapped for the different GCMs (4), SRES storylines (4) and time slices (3), resulting in 48 maps of shifted climate strata. These maps were used to place the modelled ecosystem service values in their environmental context consistently. Maps of the EnS, for baseline and the HadCM3-A2 scenario are mapped in Figure 12 for 13 aggregated Environmental Zones (EnZs).

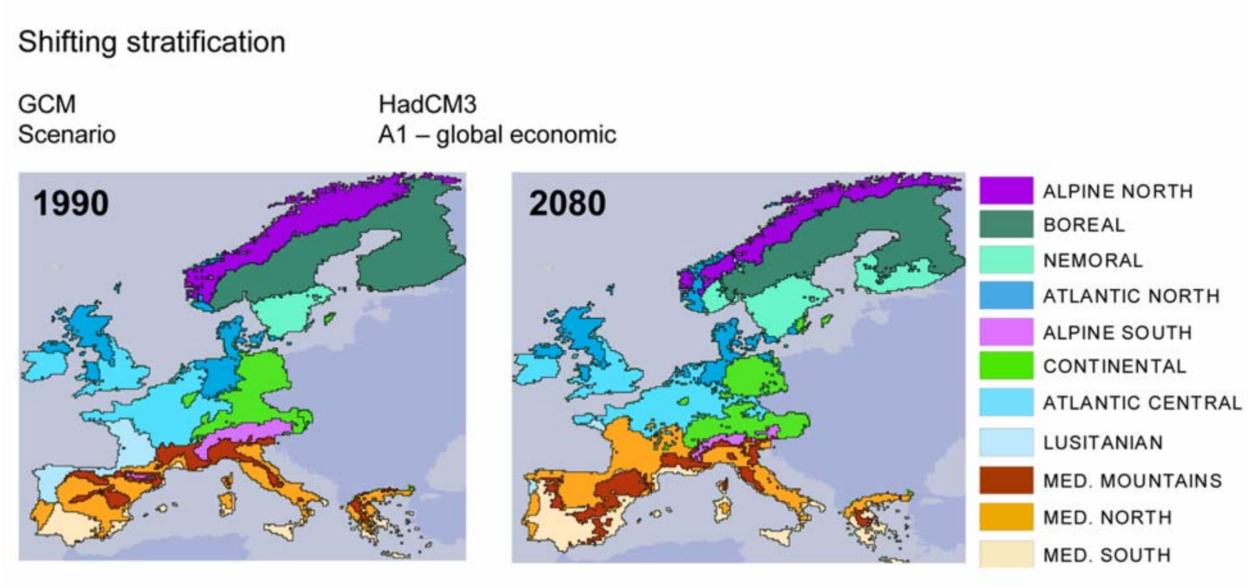


Figure 12. Climatic and topographic variables were statistically clustered into 84 environmental classes. By calculating discriminant functions for the classes they can be mapped for each global change scenario, resulting in maps of shifting climate classes that can be used for stratification. For presentation purposes, here the classes are aggregated to Environmental Zones.

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 preformed 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 (Van Ittersum 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 with a 0–1 range for ecosystem service provision 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

We thus create a map in which ecosystem services are stratified by their environment and expressed relative to a reference value (Figure 13). Because the environment changes over time, both the reference value and the environmental stratification is determined for each time slice. As shown in Figure 4, the stratified ecosystem service map shows more regional detail than the original ecosystem service map. This is the detail required to compare potential impacts across regions (see also Table 2).

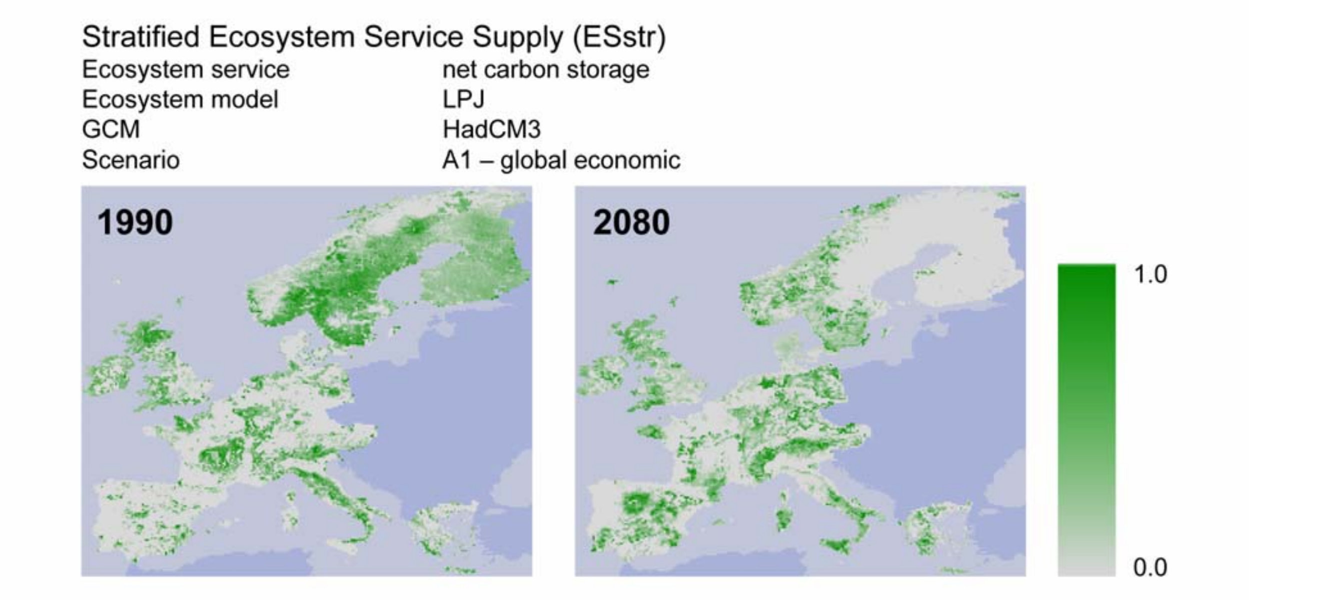


Figure 13. The modelled net carbon storage maps are stratified by the environmental strata. Stratified ecosystem service provision maps show greater regional contrast than original, un-stratified maps, because ecosystem service provision is placed in a regional instead of a continental context.

In addition to comparing regions, we want to see how the stratified sensitivities change over time. Therefore we look at three time slices through the 21st century, 2020, 2050 and 2080 as well as the 1990 baseline. The change in stratified ecosystem service provision compared to baseline, the stratified potential impact, shows how changes in ecosystem services affect a given location. Regions where ecosystem service provision relative to the environment increases have a positive stratified potential impact and vice versa. The stratified potential impact index then is:

$$PIstr(es, x, s, t) = \Delta\ ESstr(es, x, s, t) \quad (5)$$

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

PIstr is a function of both changing ecosystem service provision and the changing environmental conditions (climate). It is important to understand that PIstr does not necessarily follow the same trend as the Potential Impact, the absolute change in ecosystem service provision. If environmental conditions become less favourable for a certain ecosystem service, a certain level of decrease in ecosystem service provision would be expected, purely on this basis. When the old level of ecosystem service provision is maintained, PIstr will be positive: the ecosystem service provision relative to environmental conditions is greater than before. In Table 2, grid cell B of environment 1 has a PIstr of 0.0, because both the ecosystem service provision (ES) and ESref show a similar decrease (ES decreases by 0.2, ESref by 0.3). In the same manner, PIstr can be negative, even when in absolute terms ecosystem service provision increases. In such cases the environmental conditions become more favourable for the ecosystem service, but these more favourable conditions are not utilised. When interpreting maps of changing potential impacts or vulnerability, it is important to keep such possibilities in mind. In order to fully interpret the vulnerability of a region it is important to look not only at the vulnerability maps, but also at the constituting indictors separately.

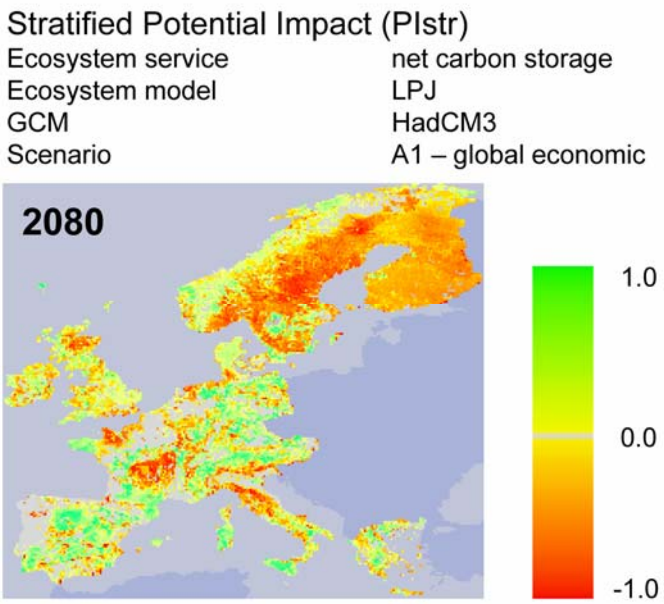


Figure 14. The change in stratified ecosystem service provision compared to baseline conditions forms a stratified measure of the potential impact for a given location. Positive values indicate an increase of ecosystem service provision relative to environmental conditions, and therefore a positive impact, while negative impacts are the result of a decrease in ecosystem service provision compared to 1990.

Adaptation

Adaptation is any adjustment in natural or human systems to a changing environment (IPCC 2001b; Table 1). Adaptation can be autonomous or planned. Autonomous adaptation is “triggered by ecological changes in natural systems and by market or welfare changes in human systems, but does not constitute a conscious response to environmental change” (IPCC 2001b). Autonomous adaptation changes sensitivity by changing a system’s state. In other words, it is part of the internal feedbacks in the human-environment system and its subsystems like ecosystems and markets, such as when forest tree species extent their bioclimatic range due to evolutionary adaptation, or the slowing of demand after price increase resulting from supply shortages. However, ecosystem models are currently hardly able to represent such system state changes, i.e. they do not dynamically model adaptive feedbacks in a coupled way (Smith et al. 1998).

Adaptation also comprises planned adaptation. Planned adaptation can take place locally, as adaptive management decisions by individuals or small planning groups, such as planting a drought resistant crop type. Furthermore, planned adaptation can be implemented on a larger or macro-scale by communities and regional representatives, such as establishing flood plains to buffer seasonal river-runoff peaks. In this study, we distinguish local scale adaptation and macro-scale adaptation, with the awareness that this separation is not always clear. Local scale adaptation is captured in the ecosystem models by taking into account local management e.g. in agriculture, forestry and carbon storage. Macro-scale adaptation enters our assessment in two ways. Broad overarching management choices based on the SRES storylines are incorporated in to the land use scenarios (Rounsevell et al. 2005) via the IMAGE model (IMAGE team 2001), which considers the impacts of climate change and CO2 concentration on, for example, crop yields and markets. Secondly, the capacity of regions for macro-scale adaptation is considered by a generic adaptive capacity index. This adaptive capacity enters the vulnerability assessment directly, and is described in the next section.

Adaptive capacity index

To capture society's ability to implement planned adaptation measures, the ATEAM project 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). The approach will be described in detail in Klein et al. 2005. 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. In our study, 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 (see above). The concept of adaptive capacity was introduced in the IPCC TAR (IPCC 2001b). According to the IPCC TAR, 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 paper has made an attempt at quantifying adaptive capacity based on observations of past hazard events (Yohe and Tol 2002). For our vulnerability assessment framework, we sought present-day and future estimates of adaptive capacity that would be quantitative, spatially explicit and based on, as well as consistent with, the exposure scenarios described above. The index of adaptive capacity we developed to meet these needs is an index of the macro-scale outer boundaries of the capacity of a region (i.e. provinces and counties) to cope with changes. 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 Figure 15, for a particular scenario (A2). Note that adaptive capacity is a function of socio-economic characteristics and is therefore also specific for each SRES scenario. Different regions in Europe show different macro-scale adaptive capacity – under this scenario, lowest adaptive capacity is expected in the Mediterranean and improves over time but large regional differences remain.

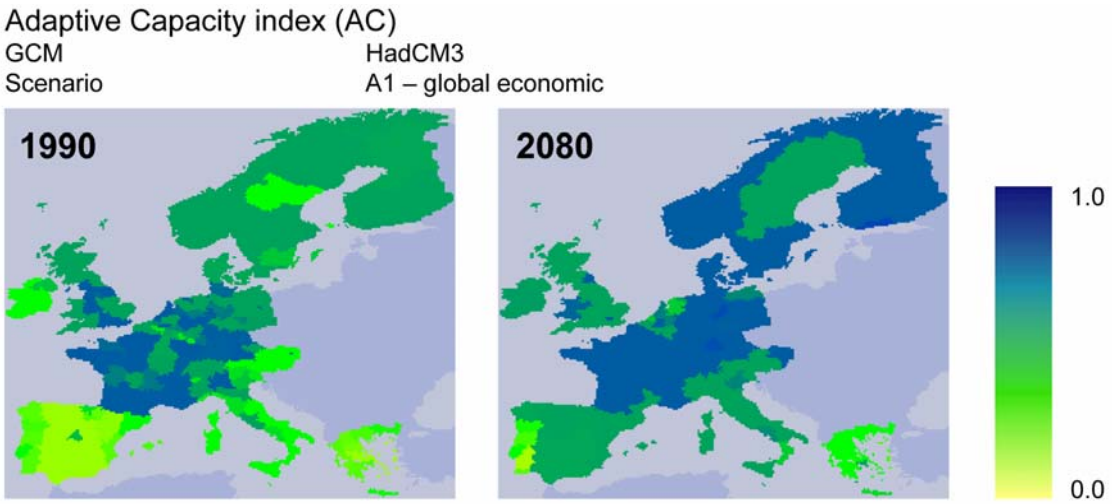


Figure 15. Socio-economic indicators for awareness, ability and action at the regional NUTS2 (provincial) level were aggregated to a generic adaptive capacity index. Trends in the original indicators were linked to the SRES scenarios

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.

Vulnerability maps

The different elements of the vulnerability function (equation 3) have now been quantified, as summarised in Figure 16. The last step, the combination of the stratified potential impact index (PIstr) and the adaptive capacity index (AC), is however the most questionable step, especially when taking into account the limited understanding of adaptive capacity. We therefore decided to create a visual combination of PIstr and AC without quantifying their intrinsic relationship. The vulnerability maps will therefore just rank the vulnerability of areas and sectors. For further analytical purposes the constituents of vulnerability, the stratified potential impact index and the adaptive capacity index, must be viewed separately.

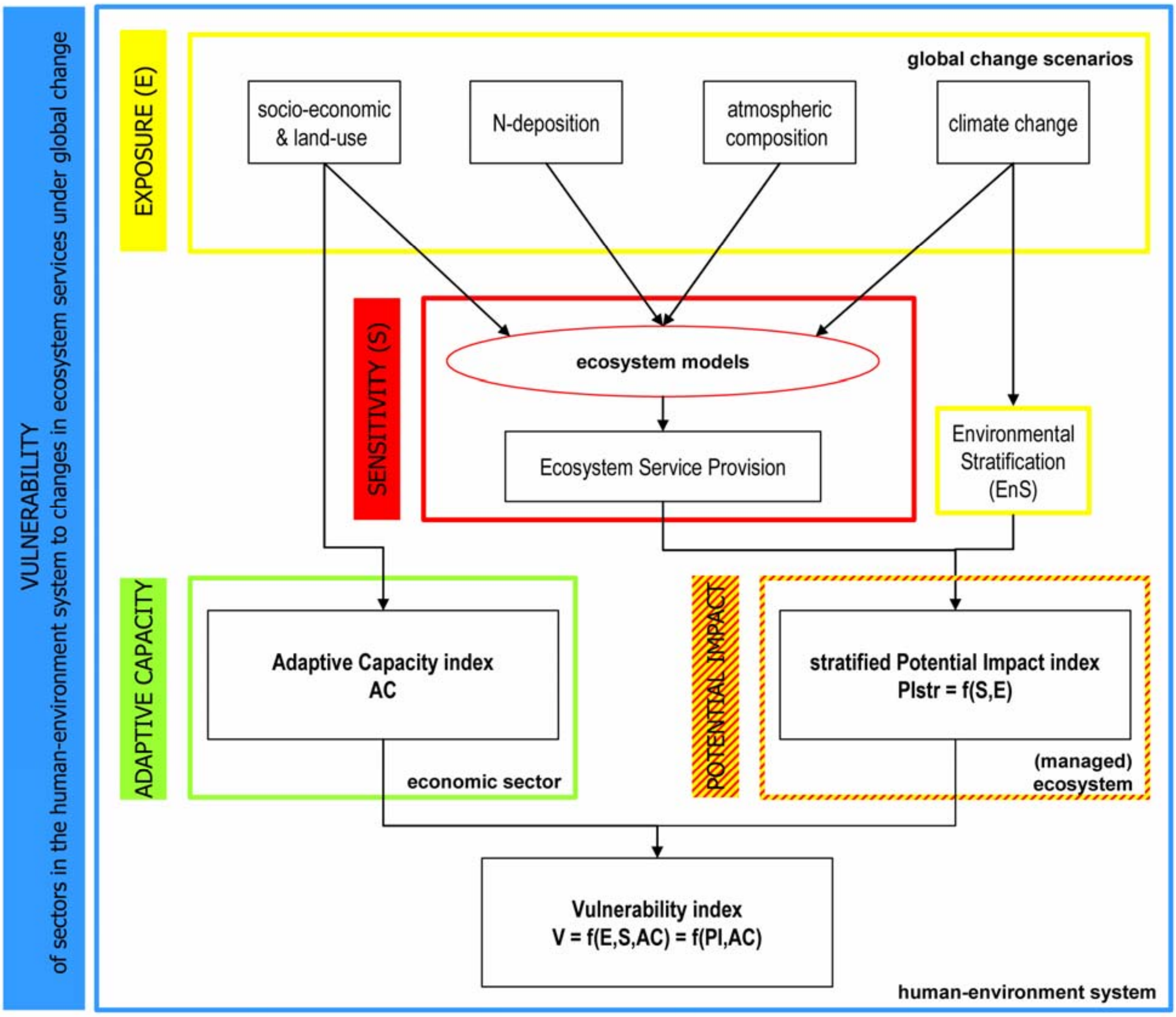


Figure 16. Summary of the ATEAM approach to quantify vulnerability. Global change scenarios of exposure are the drivers of a suite of ecosystem models that make projections for future ecosystem services provision for a 10'x10' spatial grid of Europe. The social-economic scenarios are used to project 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.

Trends in vulnerability follow the trend in potential impact: when ecosystem service provision decreases, humans relying on that particular ecosystem service become more vulnerable in that region. Alternatively, when ecosystem service provision increases, vulnerability decreases. Adaptive capacity can lower vulnerability considerably but not eliminate it completely. In regions with similar PIstr, the region with a high AC will be less vulnerable than the region with a low AC. The PIstr index determined the Hue, ranging from red (decreasing stratified 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 stratified ecosystem service provision, PIstr = 1, highest positive potential impact). The adaptive capacity index (AC) determines the colour saturation, ranging 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 provision 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. Figure 17 shows the vulnerability maps and the legend for carbon storage under the A2 scenario for the HadCM3 GCM. Under this scenario carbon storage will increase in large areas of Europe. A few regions, most notably the Boreal, parts of Scotland and the Massif Central, France, become a net source of carbon. The role of AC is apparent in the Boreal, where Finland is less vulnerable than Sweden due to a slightly higher AC, i.e. a supposed higher ability of Finland to react to these changes.

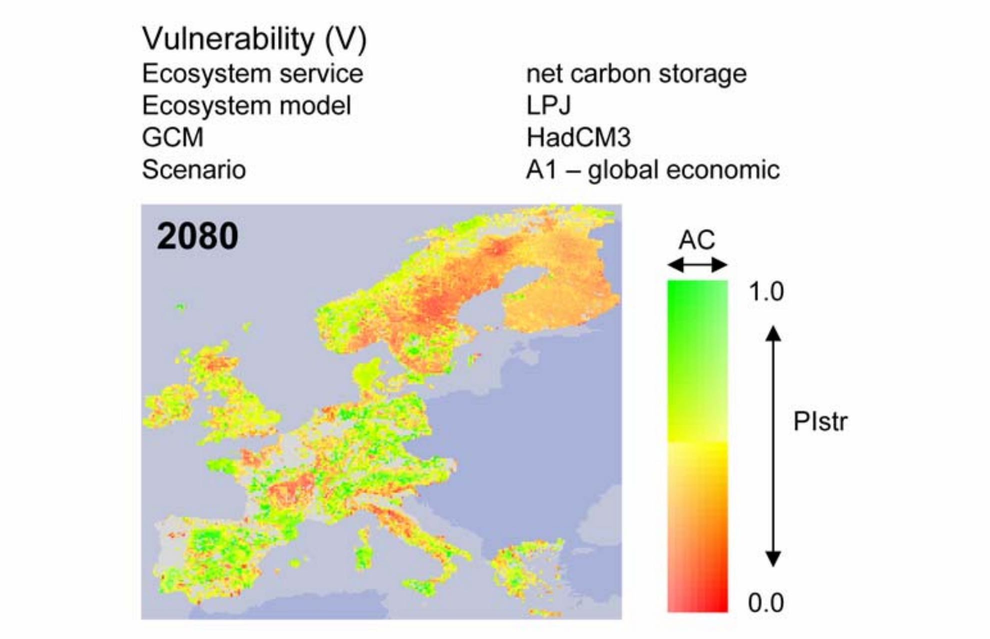


Figure 17. Vulnerability maps combine information about stratified potential impact (PIstr) and adaptive capacity (AC), as illustrated by the legend. An increase of stratified ecosystem service provision decreases vulnerability and visa versa. At the same time vulnerability is lowered by human adaptive capacity.

Analysis of vulnerability maps

Spatially modelling ecosystem services shows that global changes will impact ecosystems and humans differently across Europe. However, visual interpretation of detailed spatial patterns in maps is difficult and relies on personal judgement and experience. A multitude of maps (scenarios, time slices, GCMs) further complicates visual analysis of the maps. To make 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) or per country. Figure 18 gives an example of a summary of the changes in PIstr in 2080 for the Environmental Zones, showing the variability between

SRES storylines and GCMs. Similar graphs can be made for the other components of vulnerability, which can also be analysed separately.

Figure 18a shows that carbon storage is expected to decrease in the northern EnZs (Alpine North, Boreal, Nemoral). This is a major adverse effect. The other EnZs in all cases show an increase, with the B2 (regional environmental) scenario resulting in the largest change. Figure 18b shows that there is large variability between the GCMs. However, withstanding this variability, there remains a large difference between the northern EnZs and the others.

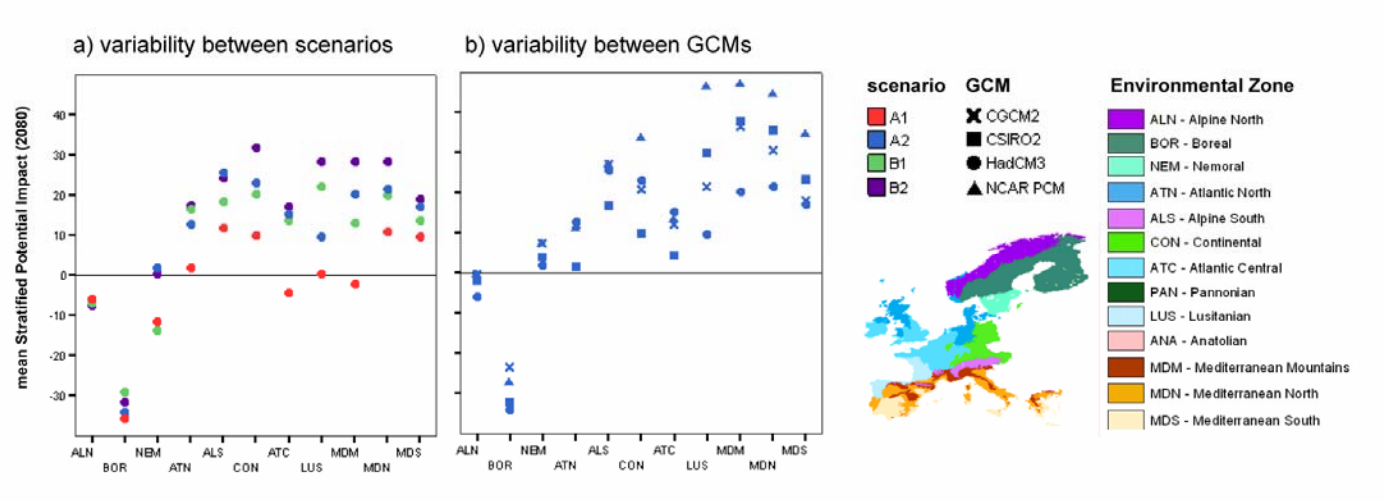


Figure 18. Scatter plots show the variability in stratified potential impact for carbon storage in 2080, summarised per Environmental Zone. The plots showing the variability between the GCMs shows that the disagreement between CGMs can be greater than the variability between the scenarios.

Discussion and conclusions

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 (e.g. socio-economic, land use, and climate change), the stakeholder involvement, and the inclusion of a measure of adaptive capacity. A novel element of the framework is the method of stratifying impacts by regional environments, which makes comparisons possible across the European environment. Furthermore, the stratification procedure allows comparison between potential impacts of diverse ecosystem services. With the approach described in this paper it is possible to perform the first comprehensive spatial vulnerability assessment for a region as large as Europe, using outputs from many different ecosystem models.

As indicated in the introduction, there is a demand for methods to integrate multidisciplinary assessments and to incorporate measures of adaptive capacity (Kasperson et al. 2001; Schröter et al. 2004; IPCC 2001a). 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, we feel that 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 has consequences for the ease of interpretation. The ATEAM mapping tool was developed to make such analyses possible. Any processing of the modelled ecosystem services adds both complexity and uncertainty. In the present approach this processing comprised of three parts. (1) The stratification of the ecosystem service maps adds considerable conceptual complexity, but is of great importance for allowing comparison across the European environment. While both the environmental stratification that is used (Metzger et al. in press) and the reference value (ESref) are essentially arbitrary, they can be applied consistently for different ecosystem services 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, prerequisite for this is a further understanding how PIstr and AC interact and influence vulnerability.

For easier explanation of our concept for a spatially explicit vulnerability assessment, this chapter uses just one ecosystem service. This suffices for illustrating the approach, but it does not allow for the analyses for which the approach was set up, i.e. comparing different ecosystem services. A complete vulnerability assessment will demonstrate the true value of the framework, not the maps of one service in isolation. The maps for net carbon storage foster a risk: for a full comprehension of the true effect of carbon storage, it is paramount to also take areas with net carbon emissions into account. However, landowners are often interested in carbon storage on its own, especially with the possibility of receiving credit for carbon storage on their land. Vulnerability maps could then help in deciding whether to use available land for carbon storage, or for another ecosystem service, e.g. bio-fuel production or forestry.

Vulnerability is a dynamic outcome of both environmental and social processes occurring at multiple scales (O'Brien et al. 2004). When the maps of vulnerability produced with our approach depict problematic regions, further attention should be directed to these regions to analyse their vulnerability in the context of nested scales and on higher and lower resolution than the 10'x10' grid. Our vulnerability maps show vulnerable areas per sector and ecosystem service, and per future time slice. Currently no model of the human-environment system exists that reflects all interactions between ecosystem services and sectors for a range of nested spatial, temporal and institutional scales. Our vulnerability maps are therefore not maps of total European vulnerability, but of some of the most essential aspects constituting it. These maps can be used to anticipate vulnerability of different sectors based on specific ecosystem services, as a basis for discussion of interactions between these sectors and ecosystem services. For example, as stakeholders from the climate protection sector have pointed out, planting forests to store carbon has implications for the other functions of a landscape, and consequently for the tourism, nature conservation or water sectors. Such qualitative information, or knowledge shared during stakeholder dialogues does not enter the approach in a formal way. Additionally, large negative impacts can be triggered by small changes and strongly alter the provisioning of ecosystem services. Sectors that are currently close to such critical thresholds want to recognize this. Such cases may be identified by stakeholders and then be subjected to more detailed analysis. Therefore it is imperative to discuss the results with stakeholders, experts and scientists as part of the analysis.

Perceived well-being, as well as anticipated vulnerability is always based on a normative value judgement. Stakeholders from different sectors may base their value judgement on different assumptions - in other words, some aspects of vulnerability are individual. In our stakeholder dialogue, it became apparent that many stakeholders are more interested in potential impacts than in generic vulnerability maps. Stakeholders used their individual values to judge the severity of a potential impact. Furthermore, stakeholders often wished to account for their own individual adaptive capacity when interpreting potential impacts. The generic adaptive capacity index we developed relayed information on the longer term socio-economic context but their anticipated ability to adapt to change remained largely a matter of personal perception. In a flood-prone area in Germany it has recently been shown that "perceived adaptive capacity" is a major determinant of whether people will take adaptation measures or not (Grothmann and Reusswig 2004). 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 and Harvey 1987).

Communication of the results of the vulnerability assessment needs 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, but also maps of the exposure, ecosystem service provision, potential impacts and adaptive capacity should always be presented as one of a range of possible scenarios. Furthermore, many of the comparisons and analyses can take place in summarised tables or graphs instead of maps, which are more easily misinterpreted. For instance, changes can be summarised per Environmental Zone (Figure 18) or per country. Similar graphs can be made for the other components of vulnerability, which can also be analysed separately. In the vulnerability mapping tool (Metzger et al. 2004) all ecosystem services of the ATEAM project can be analysed by creating such graphs. Furthermore all ecosystem services are presented in fact sheets which not only show all relevant maps, but also give important information about scenarios assumptions, modelling approach and uncertainties.

This work was guided by our wish to support stakeholders in decision-making. To enable Europe's people to decide on how to manage their land in a sustainable way, multiple maps of projected ecosystem service provision and adaptive capacity of related sectors could be obtained 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 policy makers, thereby facilitating 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

Alcamo J, Mayerhofer P, Guardans R, van Harmelen T, van Minnen J, Onigkeit J, Posch M, de Vries B (2002) An integrated assessment of regional air pollution and climate change in Europe: findings of the AIR-CLIM Project. Environmental Science & Policy 5:257-272

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

Band LE, Patterson P, Nemani R, Running SW (1993) Forest ecosystem processes at the watershed scale: incorporating hill slope hydrology. Agriculture and Forest Meteorology 63:93-126

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. 4th E.C. conference. Elsevier Applied Science, London pp 1272-1278

Carter TR, La Rovere EL, Jones RN, Leemans R, Mearns LO, Nakícenovíc N, Pittock B, Semenov SM, Skea J (2001) Developing and applying scenarios. In: McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (eds) Climate Change 2001. Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, pp 145-190

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, Vol.38, Springer-Verlag, Heidelberg 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

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

Ewert F, Rounsevell MDA, Reginster I, Metzger MJ, Leemans R (2005) Future scenarios of European agricultural land use. I: Estimating changes in crop productivity (in press)

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

Grotham T, Reusswig FID (2004) 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. in. 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

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

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

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

Karjalainen T, Pussinen A, Liski J, Nabuurs G-J, 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(1): 87-103

Kasperson JX, Kasperson RE (2001) International Workshop on Vulnerability and Global Environmental Change. Stockholm, Sweden, Stockholm Environment Institute: 36

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

Klein RJT, Schröter D., Acosta-Michlik L., Reidsma P., Metzger M.J. and Klein R.J.T., 2005. Modelling the Vulnerability of Eco-Social Systems to Global Change: Human Adaptive Capacity to Changes in Ecosystem Service Provision. In preparation to be submitted to Global Environmental Change Part A; Human and Policy Dimensions

Leemans R., van Vliet A (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

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

van der Meijden, R, van Duuren L, 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, 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

Metzger MJ, Schröter D (2005a) Concept for a spatially explicit quantitative vulnerability assessment of Europe. Submitted to Regional Environmental Change

Metzger MJ, Leemans R, Schröter D (2005) A multidisciplinary multiscale framework for assessing vulnerabilities to global change. Submitted to the Journal for Applied Geoinformation

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

Millenium Ecosystem Assessment (2003) Ecosystems and Human Well-being; a framework for assessment. Island Press, Washington

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

Mohren GMJ (2003) Large-scale scenario analysis in forest ecology and forest management. Forest Policy and Economics 5 (2): 103-110

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

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

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 (1-2):193-225

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

Petschel-Held G, Block A, Cassel-Gintz M, Kropp J, Lüdeke M, Moldehauer O, Reusswig F, Schellnhuber HJ (1999) Syndromes of global change: a qualitative modelling aproach to assist global environmental management. Environmental Modelling and Assessment 4:295-314

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 the 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

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

Sala OE, Chapin FS, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke LF, Jackson RB, Kinzig A, Leemans R, Lodge DM, Mooney HA, Oesterheld M, Poff NL, Sykes MT, Walker BH, Walker M, Wall DH (2000) Biodiversity - Global biodiversity scenarios for the year 2100. Science 287:1770-1774

Schröter D, Acosta-Michlik L, Reidsma P, Metzger MJ and 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 Fifth Open Meeting of the Human Dimensions of Global Environmental Change Research Community, Montreal, Canada. Available online http://sedac.ciesin.columbia.edu/openmtg/

Schröter D, Polsky C, Patt AG (2004) Assessing vulnerabilities to the effects of global change: an eight step approach. Mitigation and Adaptation Strategies for Global Change In press.

Schröter D., Acosta-Michlik L, Arnell AW, Araújo MB, Badeck F, Bakker M, Bondeau A, Bugmann H, Carter T, de la Vega-Leinert AC, 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 M, 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, van der Werf G, 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, pp. 139. Available at www.pik-potsdam.de/ateam.

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(2): 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, 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

Smith P, Andrén O, Brussaard L, Dangerfield M, Ekschmitt K, Lavelle P, Tate K (1998) Soil biota and global change at the ecosystem level: describing soil biota in mathematical models. Global Change Biology 4:773-784

Smith VH, Tilman GD, Nekola JC (1999) Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environmental Pollution 100:179-196

Stenseth NC, Mysterud A, Ottersen G, Hurrell JW, Chan K-S, Lima M (2002) Ecological Effects of Climate Fluctuations. Science 297:1292-1296

Tague CL, Band LE (2001) Evaluating explicit and implicit routing for watershed hydro-ecological models of forest hydrology at the small catchment scale. Hydrological Processes 15:1415-1439

Tague C, Band L (2004) Regional Hydro-Ecologic Simulation System An Object-Oriented Approach to Spatially Distributed Modelling of Carbon, Water and Nutrient Cycling. Earth Interactions (in press)

Thonicke K, Venevsky , Sitch S, Cramer W (2001) The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model. Global Ecology and Biogeography 10:661-677

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

Turner BL, Kasperson RE, Matson P, McCarthy JJ, Corell RW, Christensen L, Eckley N, Kasperson JX, Luers A, Martello ML, Polsky C, Pulsipher and 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

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

Walker B, Carpenter S, Anderies J, Abel N, Cumming GS, Janssen M, Lebel L, Norberg J, Peterson GD, Pritchard R (2002) Resilience management in social-ecological systems: a working hypothesis for a participatory approach. Conservation Ecology 6:14

Walther G-R, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin J-M, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416:389-395

Waltner-Toews D, Kay JJ, Neudoerffer C, Gitau T (2003) Perspective Changes Everything: managing ecosystems from the inside out. Frontiers in Ecology and the Environment 1:23-30

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

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

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