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The vulnerability of ecosystem services to land use change

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Abstract

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

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

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

Keywords: Vulnerability assessment; Ecosystem services; Environmental stratification; Adaptive capacity; Potential impact

1. Introduction

Many aspects of our planet are changing rapidly due to human activities and these changes are expected to accelerate during the next decades (IPCC, 2001a,b,c). For example, forest area in the tropics is declining (Geist and Lambin, 2002), many species are threatened with extinction (Thomas et al., 2004), and rising atmospheric carbon dioxide results in global warming (IPCC, 2001a,b,c). Many of these changes will have an immediate and strong effect on agriculture, forestry, biodiversity, human health and well-being, and on amenities such as traditional landscapes (Watson et al., 2000; UNEP, 2002). Furthermore, a growing global population, with

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increasing per capita consumption of food and energy, are expected to continue emitting pollutants to the atmosphere, resulting in continued nitrogen deposition and eutrophication of environments (Galloway, 2001; Alcamo, 2002). In the face of these changes, it is important to integrate and extend current operational systems for monitoring and reporting on environmental and social conditions (cf. Kates et al., 2001). Over the last decades many people have become increasingly aware of these environmental changes, such that they are now commonly recognised as ‘global change’ (Steffen et al., 2001). Many research projects and several environmental assessments are currently addressing these concerns at all relevant scales, frequently in multidisciplinary collaborations. However, integrating this wealth of information across disciplines remains a considerable challenge (Millenium Ecosystem Assessment, 2003).

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

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

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

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

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

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

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

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

2. Methods

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

2.1. The concept of vulnerability

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

$$\mathrm{V}(\mathrm{es},\mathrm{x},\mathrm{s},t) = f(\mathrm{E}(\mathrm{es},\mathrm{x},\mathrm{s},t),\mathrm{S}(\mathrm{es},\mathrm{x},\mathrm{s},t),\mathrm{AC}(\mathrm{es},\mathrm{x},\mathrm{s},t)) \tag{1}$$

$$\mathrm{PI}(\mathrm{es},\mathrm{x},\mathrm{s},t) = f(\mathrm{E}(\mathrm{es},\mathrm{x},\mathrm{s},t),\mathrm{S}(\mathrm{es},\mathrm{x},\mathrm{s},t)) \tag{2}$$

$$\mathrm{V}(\mathrm{es},\mathrm{x},\mathrm{s},t) = f(\mathrm{PI}(\mathrm{es},\mathrm{x},\mathrm{s},t),\mathrm{AC}(\mathrm{es},\mathrm{x},\mathrm{s},t)) \tag{3}$$

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

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

2.2. Exposure, sensitivity and potential impacts

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

Table 1
Definitions of important terminology related to vulnerability, with an example for the agriculture sector

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

IPCC TAR: Intergovernmental Panel on Climate Change Third Assessment Report (IPCC, 2001b).

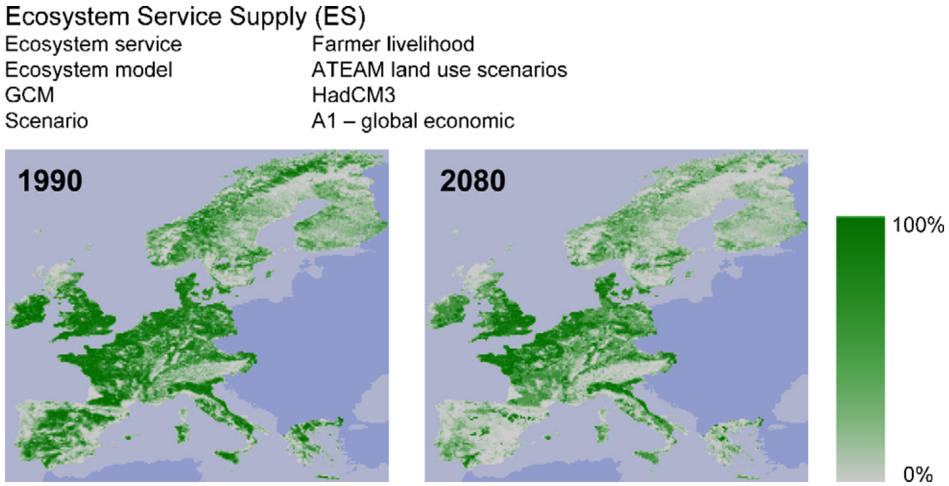

Fig. 1. Ecosystem service supply indicator for 'farmer livelihood', as modelled by the ATEAM land use scenarios for baseline conditions and the A1 scenario for the 2080 time slice.

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

In ATEAM, ecosystem service provision was estimated by ecosystem models as a function of ecosystem sensitivity and global change exposure. In this manuscript ecosystem service provision was directly linked to the land use scenarios, as discussed in Section 2.6. The resulting range of outputs for each ecosystem service indicator enabled the differentiation of regions that are impacted under most scenarios, regions that are impacted under specific scenarios, and regions that are not impacted under any scenario.

The example maps in this manuscript are restricted to the ecosystem service indicator 'farmer livelihood' (Fig. 1). For this ecosystem service indicator, the vulnerability approach is illustrated with maps for one scenario, the A1[1] scenario, which assumes continued globalisation with a focus on economic growth. In Section 2.7 the analysis of multiple scenarios is discussed.

2.3. *Stratified potential impacts*

The estimation of potential impacts is undertaken at the regional scale, emphasising the differences across the European environment. Simply comparing changes in ecosystem services across Europe provides only a limited analysis of regional differences because ecosystem services are highly correlated with their environments. Some environments have high values for particular ecosystem services, whereas other regions have lower values. For instance, Spain has high biodiversity (5048 vascular plant species (WCMC, 1992)), but low grain yields (2.7 t ha^{-1} for 1998–2000 average (Ekboir, 2002)), whereas The Netherlands has a far lower biodiversity (1477 vascular plant species (van der Meijden et al., 1996)), but a very high grain yield (8.1 t ha^{-1} for 1998–2000 average (Ekboir, 2002)). While human decisions influence regional land use more directly than broad environmental conditions, at a European scale land use is in part a function of environment (Thuiller et al., 2004; Metzger et al., 2005a). This is illustrated in Fig. 2, where agricultural land use, derived from Eurostat NewCronos agricultural statistics, is summarised for four Environmental Zones (see Fig. 3, 1990). Agriculture is almost absent in Alpine North. Grasslands and arable land dominate the Atlantic regions, with more grassland than arable land in Atlantic North and vice versa in Atlantic Central. Permanent crops cover 39% of Mediterranean South. Because of the relation between broad environment and land use, absolute differences in land use percentages are not good measures for comparing regional impacts between different European environments. Looking at relative changes would overcome this problem (e.g. −40% arable land in Mediterranean south versus +8% in the Boreal), but also has a serious limitation: the same relative change can occur in very different situations. Table 2 illustrates how a relative change of −20% can represent very different impacts, both between and within environments. Therefore comparisons of relative changes in single grid cells must be interpreted with great care.

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[1] In SRES, the A1 storyline was split in three (fi: fossil intensive; b: a mixed set and t: only renewables) to illustrate differences in emissions caused by different combinations of energy carriers. For the present analysis only A1fi, resulting in the highest emissions, was used. In the present paper A1 therefore refers to A1fi.

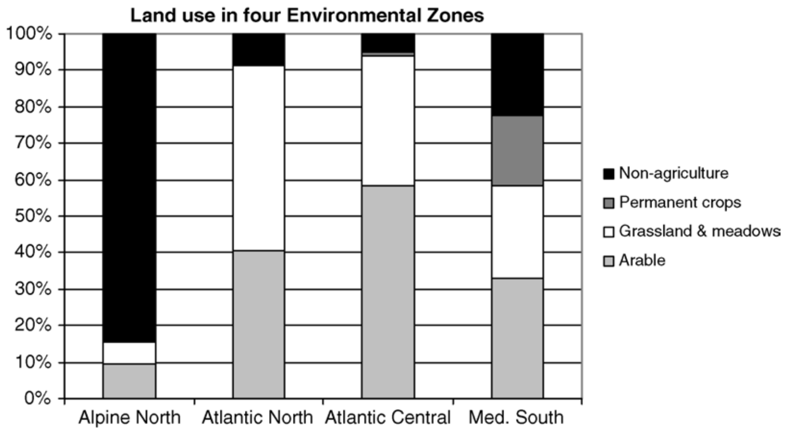

Fig. 2. Proportions of agricultural land uses in four Environmental Zones (Metzger et al., 2005a) based on Eurostat NewCronos agricultural statistics.

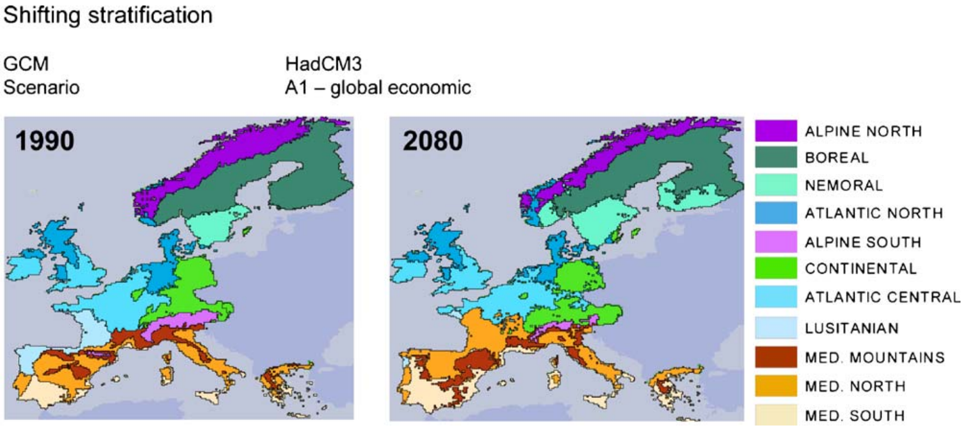

Fig. 3. Environmental Stratification of Europe (EnS), in 84 strata, here aggregated to environmental zones for presentation purposes.

For a meaningful comparison of grid cells across Europe it is necessary to place potential impacts in their regional environmental context, i.e. in an environmental envelope, or stratum, that is suited as a reference for the values in an individual grid cell. Because environments will alter under global change, consistent environmental strata must be determined for each time slice. We used the recently developed Environmental Stratification of Europe (EnS) to stratify the modelled potential impacts (Metzger et al., 2005a). The EnS was created by statistical clustering of selected climate and topographical variables into 84 strata. For each stratum a discriminant function was calculated for the variables available from the climate change scenarios. With these functions the 84 climate classes were mapped for the different GCMs, scenarios and time slices, resulting in 48 maps of shifted climate classes (Metzger, 2005). Maps of the EnS, for baseline and the HadCM3-A1 scenario are mapped in Fig. 3 for 13 aggregated environmental zones (EnZ). With these maps, all modelled potential impacts on ecosystems can be placed consistently in their environmental context.

Within an environmental stratum, ecosystem service indicators can be expressed relative to a reference value. While any reference value is inevitably arbitrary, in order to

Table 2
Example of changes in the ‘farmer livelihood’ indicator (i.e. percentage of gird cell with agricultural land use) in four grid cells and two different environments between two time slices (t and $t+1$)

	Environment 1				Environment 2			
	Grid cell A		Grid cell B		Grid cell C		Grid cell D	
	t	$t+1$	t	$t+1$	t	$t+1$	t	$t+1$
Farmer livelihood	30	24	10	8	80	64	50	40
Absolute change		−6		−2		−16		−10
Relative change (%)		−20		−20		−20		−20

Absolute change is not a suitable indicator for potential impact because it is correlated to environmental conditions. Relative change is also not a good measure because the same value (here 20%) can occur represent very different impacts.

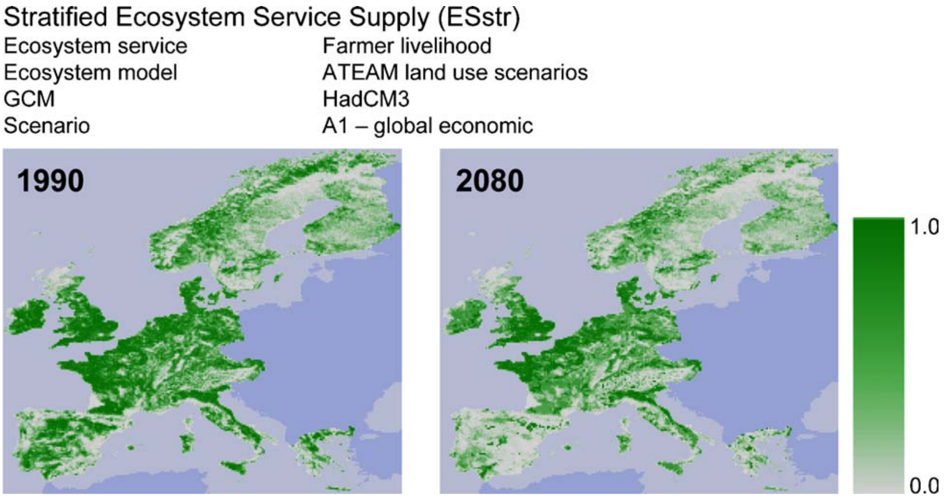

Fig. 4. Stratified ecosystem service supply for the ecosystem service indicator farmer livelihood. The ecosystem service supply maps for 'farmer livelihood' (Fig. 1) are stratified by the environmental strata (Fig. 3).

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 unitless stratified value of the ecosystem service provision (ESstr) with a 0–1 range for the ecosystem service in the grid cell (cf. Eq. (4)). Thus ESref is unique for each ecosystem service indicator, time slice, scenario, and EnS stratum:

$$\mathrm{ESstr}(\mathrm{es}, \mathrm{x}, \mathrm{s}, t) = \frac{\mathrm{ES}(\mathrm{es}, \mathrm{x}, \mathrm{s}, t)}{\mathrm{ESref}(\mathrm{es}, \mathrm{ens}, \mathrm{s}, t)} \quad (4)$$

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

In this way a map is created in which potential impacts on ecosystem services are stratified by their environment and expressed relative to a reference value (Fig. 4). Because the environment changes over time, both the reference value and the environmental stratification are determined for each time slice. As shown in Fig. 4, the stratified ecosystem service provision map shows more regional detail than the original non-stratified map. This is the regional detail required to compare potential impacts across regions (see also Table 3). The change in stratified ecosystem service provision compared to baseline conditions shows how changes in ecosystem services affect a given location (see also Table 3). Regions where ecosystem service supply increases relative to the environment have a positive change in potential impact and vice versa (see Fig. 5). This change in ESstr (Eq. (5)) gives a measure of stratified potential impact (PIstr), which is used to estimate vulnerability (see below):

$$\mathrm{PIstr}(\mathrm{es}, \mathrm{x}, \mathrm{s}, t) = \mathrm{ESstr}(\mathrm{es}, \mathrm{x}, \mathrm{s}, t) - \mathrm{ESstr}(\mathrm{es}, \mathrm{x}, \mathrm{s}, \mathrm{baseline}) \quad (5)$$

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

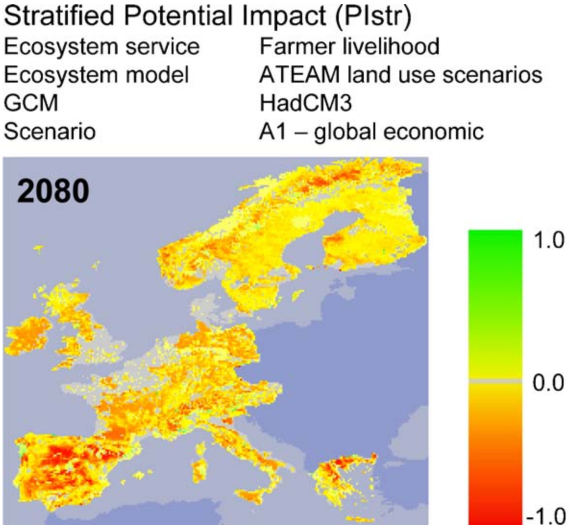

Fig. 5. Stratified potential impact for the ecosystem service indicator 'farmer livelihood'. Positive values indicate an increase of ecosystem service provision relative to environmental conditions, and therefore a positive potential impact, while negative potential impacts are the result of a relative decrease in ecosystem service provision compared to 1990.

Table 3
The environmental conditions for high farmer livelihood decreases over time in Environment 1, and increases over time in Environment 2

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

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).

2.4. Adaptive capacity index

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

1. development of a socio-economic framework using indicator-based approach;
2. estimation of future values of the indicators using regression models;
3. aggregation of the estimated values of the indicators using fuzzy models;
4. validity tests of the fuzzy models using uncertainty and sensitivity analyses.

Based on literature review, six determinants were selected as a basis for building a framework of adaptive capacity (Schröter et al., 2003; Klein et al., 2005 in preparation to be submitted to Global Environmental Change Part A: Human and Policy Dimensions). Two socio-economic indicators were used to represent each determinant of adaptive capacity. The framework thus includes 12 indicators, as indicated in Fig. 6. Time-series data for each of the 12 indicators was collected for regional administrative units of the countries in the project. Regression techniques were applied to the data to estimate the future values of the indicators for different time slices (2000, 2020, 2050, and 2080) and for each SRES storyline. Fuzzy logic was used to aggregate the estimated values of the indicators to generate the adaptive capacity index. This technique offers flexible means to assess the numerical values of the indicators through the linguistic values and soft thresholds of the membership functions (Cornelissen et al., 2001; Eierdanz et al., Mitigation and Adaptation Strategies for Global Change, submitted for publication). This flexibility is relevant for evaluating concepts such as adaptive capacity, which as yet does not have an objective yardstick to assess its relative magnitude. The validity of the fuzzy models, in particular with respect to the thresholds and gradients of the membership functions, was tested using uncertainty analysis.

An illustrative example of the developments of the adaptive capacity index over time is given in Fig. 7. Different regions in Europe show different adaptive capacities. For baseline conditions, adaptive capacity is lowest in southern European countries, which score relatively low values for the AC indicators listed in Fig. 6. Under the global economic (A1) scenario, the adaptive capacity index becomes higher across Europe, since global markets lead to positive development for most of the AC indicators (see Fig. 6). In the southern European countries some of the AC indicators increase rapidly under this scenario, e.g. in Spain 'female activity rate' is projected to rise from 35% to 60%, and in Italy there is a projected rise in the number of doctors from approximately 6 to 11 per 1000 inhabitants. Nevertheless, the adaptive capacity of the southern European countries remains lower than for northern European countries.

2.5. Vulnerability maps

The different elements of the vulnerability function (Eq. (3)) have now been quantified, as summarised in Fig. 8. The last step, the combination of the stratified potential impact (PIstr) and the adaptive capacity index (AC), is however the most difficult step, especially when taking into

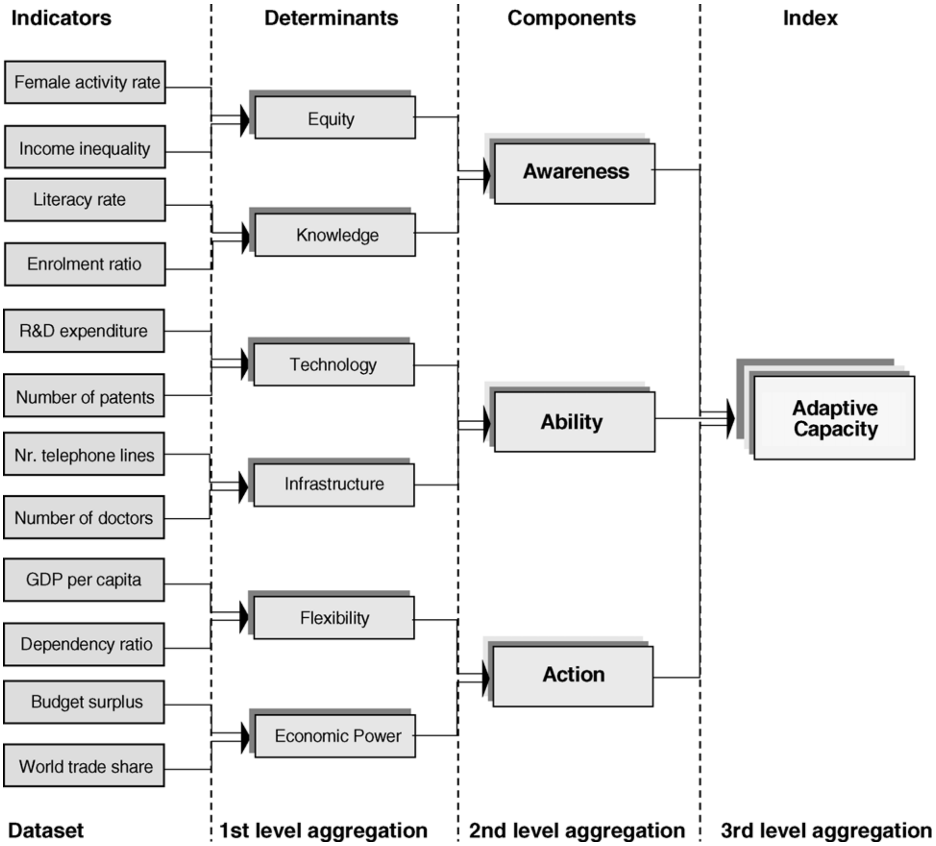

Fig. 6. Indicator framework used to develop the adaptive capacity model.

account the limited empirical basis of the adaptive capacity index. It was therefore decided to create a visual combination of PIstr and AC without quantifying a specific relationship between them. The vulnerability maps illustrate which areas are vulnerable. For further analytical purposes the constituents of vulnerability, the changes in potential impact and the adaptive capacity index, are viewed separately.

Trends in vulnerability follow the trend in PIstr: when ecosystem service supply decreases, humans relying on that particular ecosystem service become more vulnerable in that region. Alternatively, vulnerability decreases when ecosystem service supply increases. Adaptive capacity lowers vulnerability. In regions with similar changes in potential impact, a region with a high AC will be less vulnerable than a region with a low AC. The PIstr determines the Hue, ranging from red (decreasing ecosystem service provision, PIstr = −1, highest negative potential impact) through yellow (no change in ecosystem service provision, PIstr = 0, no potential impact) to green (increase in ecosystem service

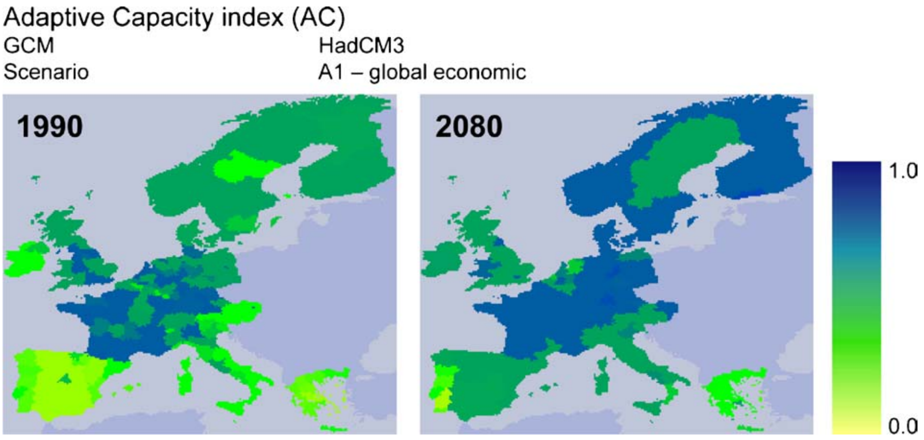

Fig. 7. Socio-economic indicators have been aggregated to a generic adaptive capacity index. Trends in the original indicators were linked to the SRES storylines in order to map adaptive capacity in the 21st century.

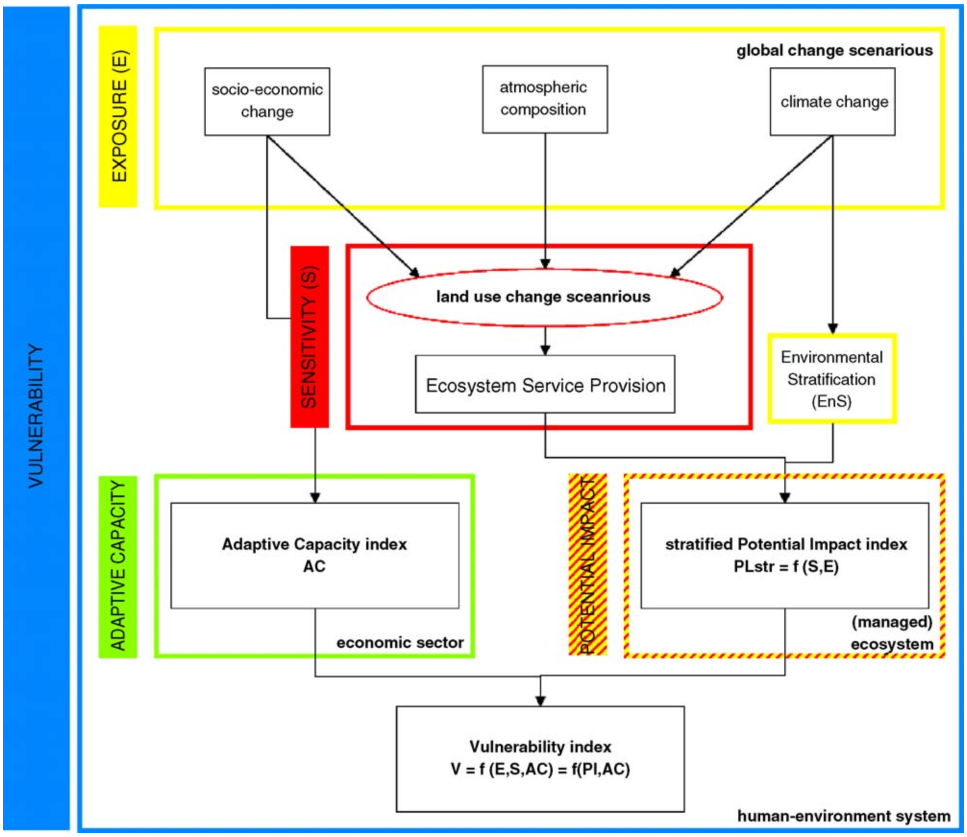

Fig. 8. Summary of the ATEAM approach to quantify vulnerability. Global change storylines and scenarios were used to produce the land use change scenarios. These were linked to several ecosystem service indicators, and provide maps of ecosystem services provision for a $10' \times 10'$ spatial grid of 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.

provision, PIstr = 1, highest positive potential impact). Note that it is possible that while the modelled potential impact remains unchanged, the stratified potential impact increases or decreases due to changes in the highest value of ecosystem service supply in the environmental class (ESref). Thus, when the environment changes, this is reflected in the potential impact.

Adaptive capacity determines colour saturation and ranges from 50% to 100% depending on the level of the AC. When the PIstr becomes more negative, a higher AC will lower the vulnerability, therefore a higher AC value has a lower saturation, resulting in a less bright shade of red. Alternatively, when ecosystem service supply increases (PIstr > 0), a higher AC value has a higher saturation, resulting in a brighter shade of green. Conversely, in areas of negative impact, low AC gives brighter red, whereas in areas of positive impacts low AC gives less bright green. Fig. 9 shows the vulnerability maps and the legend for ‘farmer livelihood’ under the A1 scenario for the HadCM3 GCM. Under this scenario farmer livelihood decreases in extensive agricultural areas. The role of AC becomes apparent in rural

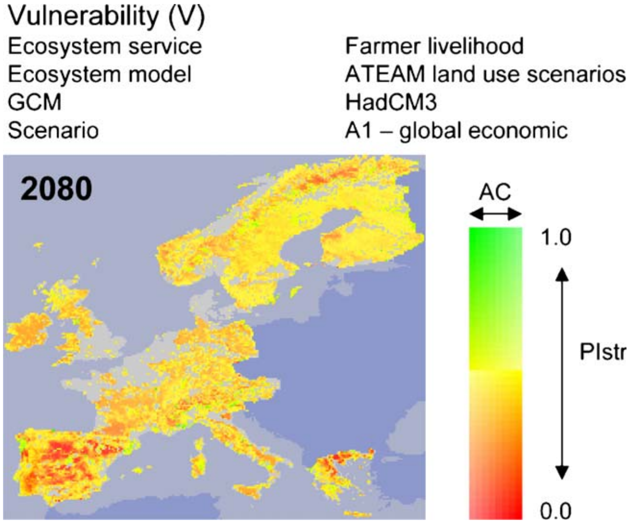

Fig. 9. Vulnerability maps for the ecosystem service indicator ‘farmer livelihood’. These maps combine information about stratified potential impact (Fig. 5) and adaptive capacity (Fig. 6), as illustrated by the legend. An increase of potential impact decreases vulnerability and visa versa. At the same time vulnerability is lowered by human adaptive capacity.

Table 4
The relationship between ATEAM land use types (Rounsevell et al., this volume) and five ecosystem service indicators

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

France and Spain, where France is less vulnerable than Spain due to a higher AC, i.e. a supposed higher ability of the French agricultural sector to react to these potential impacts.

2.6. *Land use services*

The ATEAM land use change scenarios (Rounsevell et al., this volume) were developed with the aim of supporting the types of vulnerability assessments presented here. Within ATEAM, different ecosystem models were run with these scenarios to give insights into the potential impacts of global change for different European sectors. The ecosystem service indicators calculated by these models were analysed with the vulnerability methodology described in the previous sections (Metzger et al., 2004). This section describes how ecosystem service indicators can also be derived directly from the land use change scenarios. Results from the analysis of such indicators help in understanding the vulnerability of ecosystem services to land use change.

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

The provision of many ecosystem services relies directly on land use. For instance, food production relies on agricultural land use, wood production on forestry, and outdoor recreation on attractive landscapes. Table 4 shows how the different land use types from the ATEAM scenarios were aggregated to create indicators for five ecosystem services. These indicators are described briefly below.

2.6.1. *Fibre, energy and regional food production*

These provisioning ecosystem services are most easily associated with types of land use. Food production can be directly related to agricultural land use, fibre production to forestry and cropland and energy production to the area used for bio-energy crops, as indicated in Table 4. The actual ecosystem service provision, in crop yield or timber increment, greatly depends on biophysical growing conditions. However, as discussed in Section 2.3, in order to compare ecosystem services across Europe, differences caused by inherently different environments were removed using the stratification. Therefore, for the vulnerability concept used here, the land use types form appropriate indicators for ecosystem service provision.

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

2.6.2. *Farmer livelihood*

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

2.6.3. Outdoor recreation

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

2.7. Analysis of the results

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

3. Results and discussion

3.1. Adaptive capacity

The capacity of different countries and regions in Europe to cope with the effects of global change is projected to increase in the coming century. Regression analysis of time-series data for the AC indicators (Fig. 6) indicated a positive relation between gross domestic product (GDP) and the indicators. Therefore, the assumed economic growth is expected to have a positive influence on AC. While GDP growth is projected for all countries, countries that currently have a lower adaptive capacity (e.g. the Mediterranean countries) are most able to utilise the projected increase in wealth to substantially increase macro scale adaptive capacity (Fig. 10). In these regions, increased wealth is projected to have direct effects on the determinants of AC, as illustrated for the indicators ‘female activity rate’ and ‘number of doctors’ in Section 2.4. Countries that already show a large AC will also benefit form a growing awareness of global change impacts, but to a lesser degree, as shown in Fig. 10. In some cases, a decreasing population trend will negatively affect flexibility, and thus AC. By the end of the century, the differences in AC across Europe converge. Nevertheless, there is still considerable variation, with larger AC in northern regions and lower AC in the Mediterranean countries, as shown in Fig. 11. For these countries, the development pathways associated with the scenarios have a large influence. The A1 (global-economic) scenario projects the greatest increase in AC, while the B2

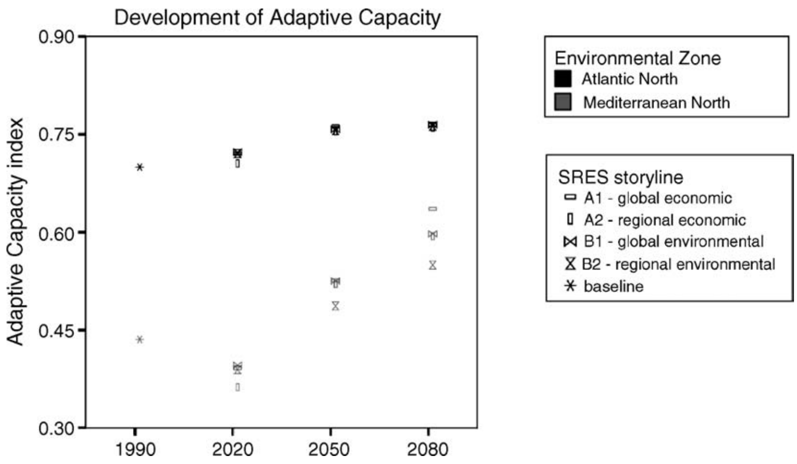

Fig. 10. Scatter plot showing the development of adaptive capacity (AC) in two Environmental Zones for the four SRES storylines. Although AC increases much more rapidly in the Mediterranean North than in the Atlantic North, toward the end of the 21st century AC is still considerable higher in Atlantic North.

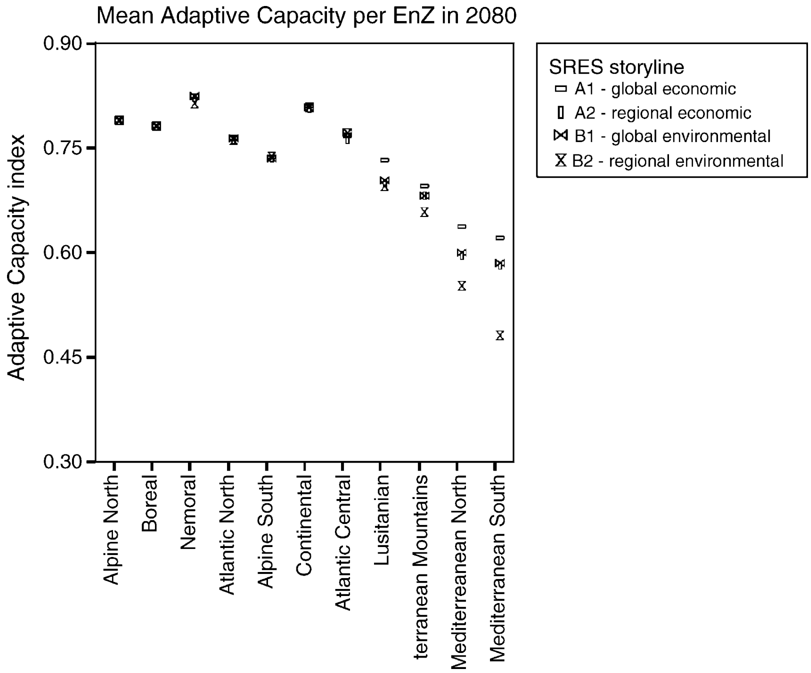

Fig. 11. Scatter plot of the mean adaptive capacity (AC) per Environmental Zone (EnZ) in 2080 for the four SRES storylines. AC in southern Europe is projected to remain lower than in northern Europe. The direction of future development is more important for AC in southern Europe than in northern Europe.

(regional-environmental) scenario is associated with lower adaptive capacity.

3.2. Potential impacts

The stratified potential impacts (PIstr) are summarised per ecosystem service indicator, in a similar manner to adaptive capacity (Fig. 12). In order to further facilitate interpretation, PIstr is classified into five categories, based on the full range of values. The classes range from very positive impacts (PIstr > 0.15), positive impacts (PIstr between 0.05 and 0.15), neutral (PIstr between 0.05 and -0.05), negative (PIstr between -0.05 and -0.15), and very negative (PIstr < -0.15). The scatter plots in Fig. 12 can now be used to (1) compare the impacts on the different ecosystem service indicators, (2) compare the impacts between regions, and (3) compare the influence of the SRES scenarios. The conclusions of these three analyses are used to draw more general conclusions about the vulnerability of the ecosystem service indicators to land use change.

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

Fig. 12 shows that PIstr for energy production and outdoor recreation is positive or very positive for most regions in Europe. For the other ecosystem service indicators there is heterogeneity in the impacts between different regions of Europe. There appears to be a trend towards more negative PIstr for more southern environmental zones (EnZs). Especially the Mediterranean EnZs have many ‘very negative’ PIstr scores.

There is a strong influence of the SRES scenarios on PIstr. Nevertheless, the direction of PIstr, positive or negative, is not influenced by the scenarios. Strong economic development (the A scenarios), is associated with the largest land use changes (Rounsevell et al., this volume), which translates into more extreme impacts than the scenarios associated with environmentally focused development (the B scenarios). Mediterranean North and South both face very negative impacts for regional food production, farmer livelihood, and fibre production under the A1 scenario. In Fig. 12, there does not appear to be a clear signal differentiating the global and regional scenarios (1 and 2, respectively). This is an artefact of the aggregation into five classes. In the original data a differentiation can be found, with lower impacts for the regionally oriented scenarios. However, the difference is far smaller than the differentiation between the A-, B-scenarios, and not distinct enough to appear in the aggregation.

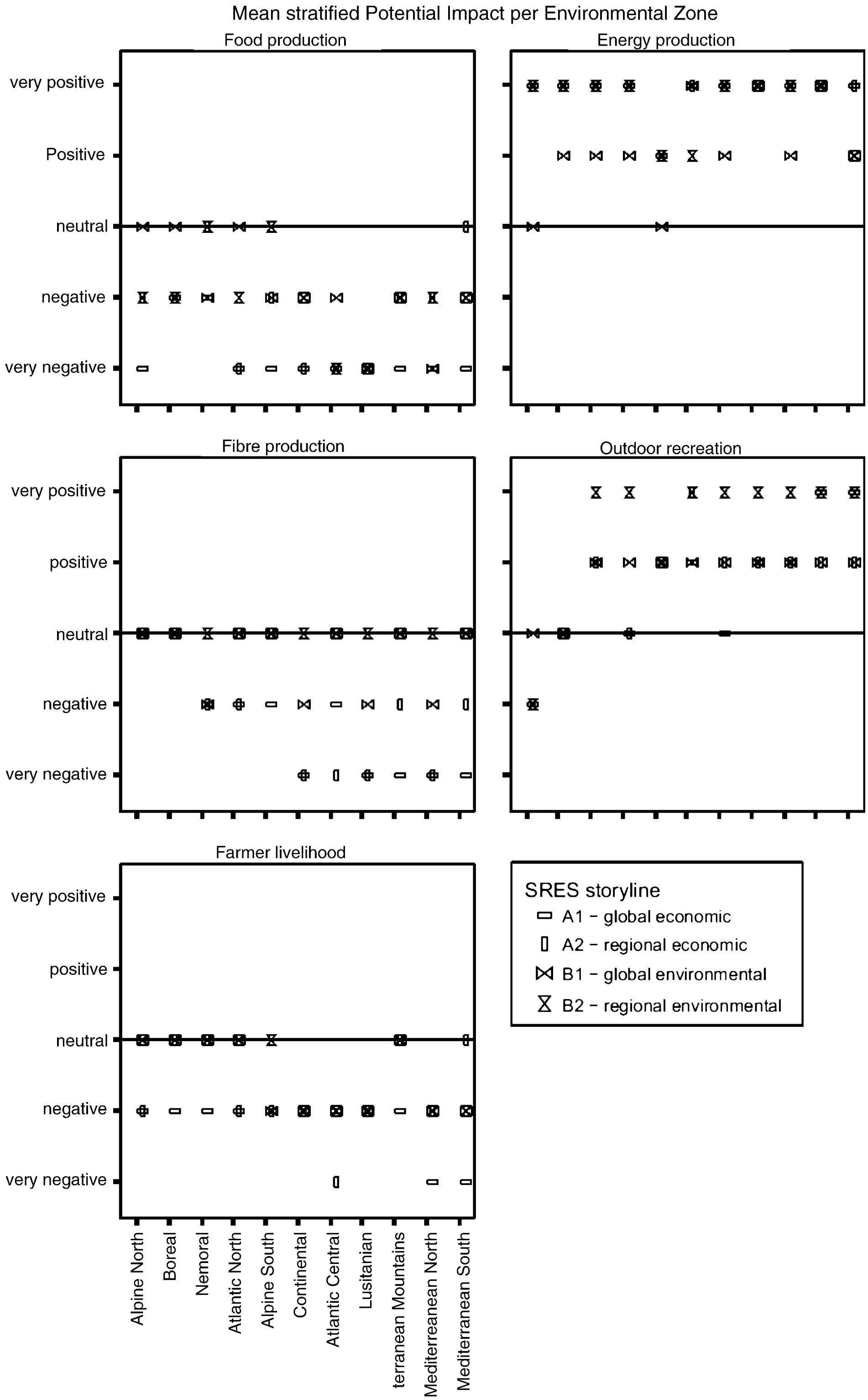

Fig. 12. Five scatter plots showing stratified potential impact (PIstr) of ecosystem service indicators, in five categories, per Environmental Zone for the SRES storylines. These plots illustrate the differences between ecosystem services, the variability across the European environment, and the influence of the SRES storylines.

3.3. Vulnerability

Adaptive capacity and potential impact are quantified and analyzed for the principal European Environmental Zones (in Figs. 10 and 12, respectively). By combining the findings from these graphs it is possible to make some general statements about the vulnerability of the ecosystem services to land use change, without quantifying the relative contribution of PI and AC.

The northern EnZs (Alpine North, Boreal, Nemoral, Atlantic North) are projected to have a high AC under all SRES scenarios (Fig. 10). Furthermore, PIstr reaches the ‘very negative’ category in just 3 of the 48 possible combinations of EnZ (4), scenario (4) and ecosystem service (3, which have negative impacts) (see also Fig. 11). From this we can conclude that northern Europe is less likely to be vulnerable to projected land use changes. The ecosystem service indicators that rely on agricultural land uses do show a negative PIstr, but the high level of AC compensates for this in the final vulnerability. Conversely, southern EnZs (Lusitanian, Mediterranean zones) have a lower AC than the northern regions (Fig. 10) and PIstr reaches the ‘very negative’ category in 16 of the 48 possible combinations. Southern Europe, therefore, seems considerably more vulnerable than Northern Europe, especially for ecosystem services relying on agriculture.

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

3.4. Land use scenarios in vulnerability assessment

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

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

3.5. Assumptions and uncertainties

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

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

For the present study, simplistic assumptions were made in order to link the ATEAM land use scenarios to different ecosystem services (cf. Table 4). These ecosystem service indicators are not very specific, and groups relying on these ecosystem services are heterogeneous. For instance, for mountaineers and hunters the outdoor recreation indicator could be of interest. However, the mountaineer will not be interested in expansion of forest area, which will affect the indicator. Other indicators can lead to similar interpretation problems. It is therefore important to communicate to stakeholders what the indicators entail.

The stratification adds additional conceptual complexity to the vulnerability framework, but is of importance for allowing comparison across the European environment. The environmental stratification that was used (Metzger et al., 2005a; Metzger, 2005) is based on the ATEAM climate change scenarios. Some additional uncertainty is added by the statistical classification, as discussed by Metzger et al. (2005a) and Metzger (2005). However one of the more profound assumptions for the present study is the choice of the reference values (ESref). Any reference value that can be applied consistently across different ecosystem services will necessarily be arbitrary. The choice for the highest value of the ecosystem service indicator with the EnS stratum was based on the conceptual notion that potential values of the indicator is restricted by environmental constraints. While this works well for ecosystem indicators that are directly correlated with wider environmental or climatic patterns, it could have significant implications when the maximum value in an outlier within the stratum. However, for the land use indicators in the present study, the potential range of values for the indicators is restricted by the fact that grid cells cannot be covered by more than 100%.

The adaptive capacity indicator framework forms the first scenario-based model of adaptive capacity. It forms a good basis for discussion on the future ability to cope with projected changes, but it is based on several uncertain assumptions. Firstly, the conceptual indicator framework (Fig. 6), while based on current scientific understanding of AC, is in part arbitrary, and changes in the choice of indicators could influence the outcome of the indicator. A second major source of uncertainty is the assumption that historical trends in the relation between the 12 indicators of AC and GDP and population, based on time-series data for the last 30 years, will remain the same in the 21st century. Finally, there are uncertainties associated with the fuzzy aggregation of the 12 indicators to a single index. Validation of the adaptive capacity index is difficult, or perhaps impossible, making it difficult to quantify uncertainties.

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

3.6. *Limitations in the approach*

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

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

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

3.7. Possible future developments and improvements

The present approach was developed for the ATEAM project, but could equally well be used in other assessments. Metzger et al. (2005b) have shown how biomes can be used to stratify ecosystem service indicators from the global model IMAGE (IMAGE Team, 2001). There are two limitations to applying the complete vulnerability framework to other modelling studies: both a quantitative stratification and some measure of adaptive capacity need to be available. For European assessments such (e.g. EURURALIS (Klijn et al., 2005)) this should not pose too much of a problem, as the datasets used in the presented study could be used. For other regions, such datasets may need to be developed. Application of the vulnerability framework to global change impacts in the arctic region are currently under discussion.

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

4. Conclusions

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

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