Reg Environ Change
DOI 10.1007/s10113-008-0044-x

ORIGINAL ARTICLE

A spatially explicit and quantitative vulnerability assessment of ecosystem service change in Europe

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Received: 31 July 2007 / Accepted: 7 December 2007

Abstract Environmental change alters ecosystem functioning and may put the provision of services to human at risk. This paper presents a spatially explicit and quantitative assessment of the corresponding vulnerability for Europe, using a new framework designed to answer multidisciplinary policy relevant questions about the vulnerability of the human-environment system to global change. Scenarios were constructed for a range of possible changes in socio-economic trends, land uses and climate. These scenarios were used as inputs in a range of ecosystem models in order to assess the response of ecosystem function as well as the changes in the services they provide. The framework was used to relate the impacts of changing ecosystem service provision for four sectors in relation to each other, and to combine them with a simple, but generic index for societal adaptive capacity. By allowing analysis of different sectors, regions and development pathways, the vulnerability assessment provides a basis for discussion between stakeholders and policymakers about sustainable management of Europe's natural resources.

Keywords Vulnerability assessment · Global change · Ecosystem services · Adaptive capacity · Europe

Electronic supplementary material The online version of this article (doi:10.1007/s10113-008-0044-x) contains supplementary material, which is available to authorized users.

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Introduction

Many facets of current global change have documented immediate and strong effects on the natural environment, including agriculture, forestry, watercourses; on cultural values such as traditional landscapes, as well as on human health and well being (Watson et al. 2000; UNEP 2002; Reid et al. 2005). Furthermore, a globally growing human population, with increasing per capita consumption of food and energy, is 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 (Kates et al. 2001). Both research projects and also more operational environmental assessments are currently addressing these concerns at all relevant scales, frequently in multidisciplinary collaborations. However, integrating the information across disciplines remains a considerable challenge (Millennium Ecosystem Assessment 2003).

The concept of "ecosystem services" forms a useful link between the functioning of ecosystems and their role for society. A recent implementation distinguishes provisional services (e.g. food, timber, medicines and fuels), regulating services (e.g. climate regulation and water purification), cultural services (e.g. aesthetic values and sense of place) and supporting services (e.g. nutrient cycling and climate regulation) (Daily 1997; Millennium Ecosystem Assessment 2003). The advantage of this concept is that most services can be quantified, even if no single metric is applied across their entire range. Impacts of global change, including land use change, on ecosystems have been observed (see reviews by Geist and Lambin 2002; Parmesan and Yohe 2003; Root et al. 2003; IPCC 2007) and affect human society. In addition to immediate global change effects on humans (e.g. sea-level rise or droughts), an important part of human vulnerability to global change is therefore caused by impacts on ecosystems and the services they provide (Millennium Ecosystem Assessment 2003).

The synthesis chapter (Smith et al. 2001) of the Intergovernmental Panel on Climate Change (IPCC) third assessment report (TAR) recognized the limitations of traditional impact assessments, where a few climate-change scenarios are used to assess the response of a system at a future time. Smith et al. (2001) challenged the scientific community to move toward more transient assessments that are functions 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.

Although this definition addresses climate change only, it includes susceptibility, which is a function of exposure, sensitivity and adaptive capacity. The vulnerability concept developed here (in the context of the EU Framework Five Project ATEAM) is an elaboration of this definition as well as an implementation of it. It was developed especially to integrate results from a broad range of models and scenarios (Schröter et al. 2005a). Projections of changing supply of different ecosystem services and scenario-based changes in adaptive capacity are integrated into vulnerability maps for different socio-economic sectors (agriculture, forestry, climate regulation and nature conservation) (Metzger and Schröter 2006; Metzger et al. 2004, 2005a, 2006). This paper demonstrates how these vulnerability maps provide a mean 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 certain region?
- Which scenario is the least harmful for a sector?

The following sections first summarise the concepts of the spatially explicit and quantitative framework for a vulnerability assessment for Europe. Then, results from the assessment are presented. First, per socio-economic sector, then, per principal European environmental zone (e.g. comparing impacts between the Atlantic and the Mediterranean).

Methods

The ATEAM methodology for a spatially explicit and quantitative vulnerability assessment for global environmental change in Europe is described in detail by Metzger and Schröter (2006). We here focus on the conceptual foundations and their rationale.

The concept of vulnerability

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

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

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

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

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

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

Table 1 Definitions of important terminologies related to vulnerability, with an example for the carbon storage sector

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 a better fire management
Vulnerability (V)	The degree to which an ecosystem service is sensitive to global change + 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

IPCC TAR Intergovernmental panel on climate change third assessment report (IPCC 2001)

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 emphasises a largely different set of social and economic development pathways, organised along two axes. The vertical axis represents a distinction between (A) more economically and (B) more environmentally and equity orientated futures. The horizontal axis represents the range between (1) more globalisation and (2) more regionally oriented developments. A summary of the storylines based on Ewert et al. (2005) and Rounsevell et al. (2006), as well as regional summaries of the climate and land use scenarios, are provided as supplementary material to this paper.

Scenarios were developed for atmospheric carbon dioxide concentration, climate (Mitchell et al. 2004), socio-economic variables and land use (Rounsevell et al. 2006). These scenarios are internally consistent, and considered explicitly the global context of European land use (i.e. import and export of agricultural goods). The IMAGE implementation (IMAGE team 2001) of these scenarios was used to define the global context (trade, socio-economic trends, demography, global emissions and atmospheric concentrations, climate change levels). The high-resolution (10 arcmin × 10 arcmin, approximately, 16 × 16 km in Europe) land use change scenarios used in this vulnerability assessment were derived from an interpretation of the SRES storylines. Rounsevell et al. (2006) discuss the ATEAM scenarios in more detail. The vulnerability assessment spans a wide range of plausible futures for three time slices (1990–2020, 2020–2050, 2050–2080).

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

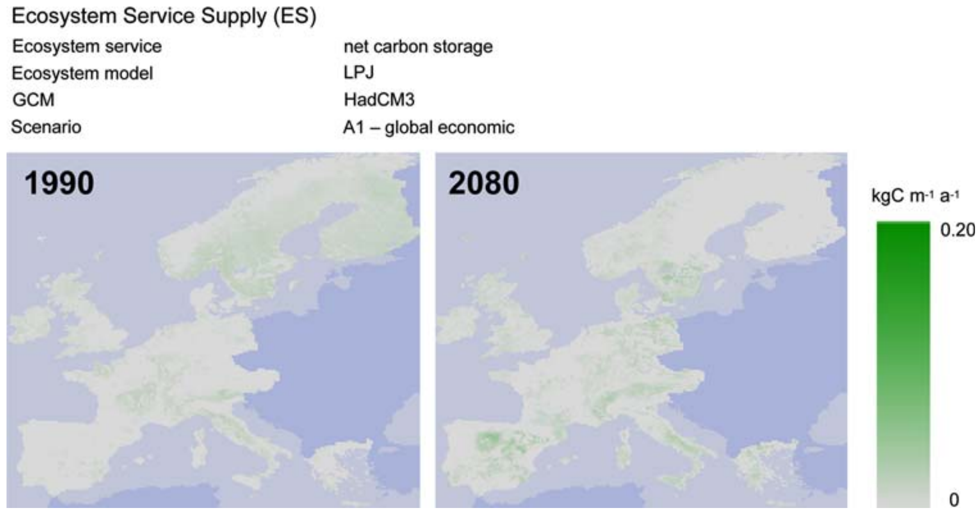

Fig. 1 Net carbon storage across Europe as modelled by the LPJ model for the A2 scenario and the HadCM3 GCM for climate and land use change. *Grey areas* are net sources of carbon. Carbon emission is not mapped here because in the vulnerability framework-ecosystem services and antagonist disservices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

The example maps in this manuscript are restricted to the ecosystem service indicator net carbon storage (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. The analysis of multiple scenarios is discussed at the end of this section.

Stratified potential impacts

The estimation of potential impacts is undertaken at the regional scale, emphasising the differences across the European environment. Simply comparing changes in ecosystem services across Europe provides only a limited analysis of regional differences because ecosystem services are highly correlated with their environments. Some environments have high values for particular ecosystem services, whereas other regions have lower values. For instance, Spain has high biodiversity, but low grain yields, whereas The Netherlands has a far lower biodiversity, but a very high grain yield. Therefore, while providing useful information about the stock of resources at a European scale, absolute differences in species numbers or yield levels are not good measures for comparing regional impacts between these countries. Looking at relative changes would overcome this problem (e.g. −40% arable land in Mediterranean south vs. +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.

For a meaningful comparison of grid cells across Europe, it is necessary to place potential impacts in their regional environmental context, i.e. in an environmental envelope, or stratum, that is suited as a reference for the values in an individual grid cell. Because environments will alter under global change, consistent environmental strata must be determined for each time slice. The recently developed environmental stratification of Europe (EnS) was used to stratify the modelled potential impacts (Metzger et al. 2005b; Jongman et al. 2006). The EnS was created by statistical clustering of selected climate and topographical variables into 84 strata. For each stratum, a discriminant function was calculated for the variables available from the climate change scenarios. With these functions, the 84 climate classes were mapped for the different Global Climate Models (GCMs), scenarios and time slices, resulting in 48 maps of shifted climate classes (Metzger et al. 2008). Maps of the EnS, for baseline and the HadCM3–A1 scenario are mapped in Fig. 2 for 11 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 make comparisons, it is important that the stratification is performed consistently. The reference value used in this assessment is the highest ecosystem service value achieved in an environmental stratum. This measure can be compared to the concept of potential yield, defined by growth-limiting environmental factors (Van Ittersum et al. 2003). For a grid cell in a given EnS stratum, the fraction of the

[1] In SRES, the A1 storyline was split in to 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 this paper, A1 therefore refers to A1fi.

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)

	Environment 1				Environment 2			
	Grid cell A		Grid cell B		Grid cell C		Grid cell D	
	t	t + 1	t	t + 1	t	t + 1	t	t + 1
Ecosystem service provision (ES)	3.0	2.4	1.0	0.8	8.0	6.4	5.0	4.0
Absolute change		−0.6		−0.2		−1.6		−1.0
Relative change (%)		−20		−20		−20		−20
Highest ecosystem service value (ESref)	3.0	2.7	3.0	2.7	8.0	8.8	8.0	8.8
Stratified ecosystem service provision (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

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 examplem, it is always −20%. When changes are stratified by their environment, comparison of potential impacts in their specific environmental context is possible. The "stratified potential impact" is the "value in a grid cell" divided by the "highest ecosystem service value" in a specific environmental stratum at a specific time slice (see text). Note that in grid cell B, PIstr is 0.0 even though ES decreases because relative to the environmental condition, ecosystem service provision is constant (see text)

modelled ecosystem service provision relative to the highest achieved ecosystem service value in the region (ESref) is calculated, giving a stratified value of the ecosystem service provision (ESstr) with a 0–1 range for the ecosystem service in the grid cell:

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

where ESstr is the 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 and t a time slice and ens an environmental stratum.

In this way, a map is created, in which, potential impacts on ecosystem services are stratified by their environment and expressed relative to a reference value (Fig. 3). Because the environment changes over time, both the reference value and the environmental stratification are determined for each time slice. As shown in Fig. 3, the stratified ecosystem service provision map shows more regional detail than the original non-stratified map. This is the regional detail required to compare potential impacts across regions (see also Table 2). The change in stratified ecosystem service provision compared to baseline conditions shows how changes in ecosystem services affect a given location (see also Table 2). Regions where ecosystem service supply increases relative to the environment have a positive change in potential impact and vice versa (see Fig. 4). This change in ESstr (Eq. 5) gives a measure of stratified potential impact (PIstr), which is used to estimate vulnerability (see below).

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

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

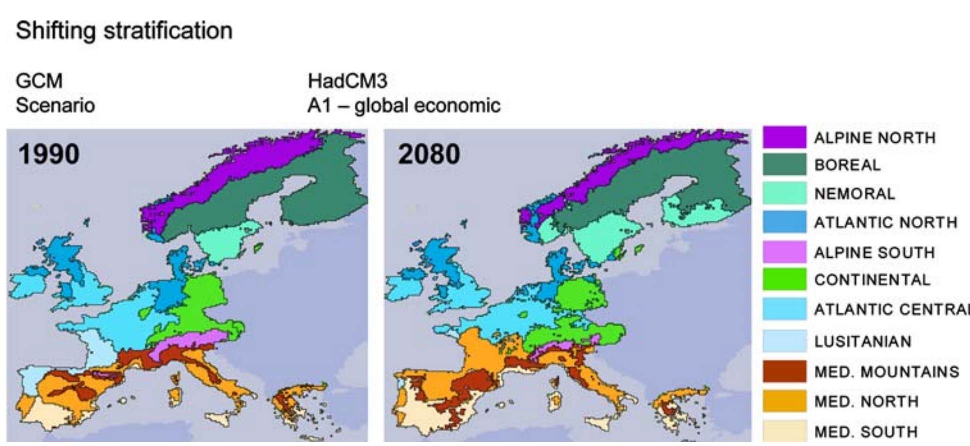

Fig. 2 Climatic and topographic variables were statistically clustered into 84 environmental strata. By calculating discriminant functions for the strata, they can be mapped for each global change scenario, resulting in maps of shifting climate strata that can be used for stratification (Metzger et al. 2008). For presentation purposes, here the strata are aggregated to 11 environmental zones

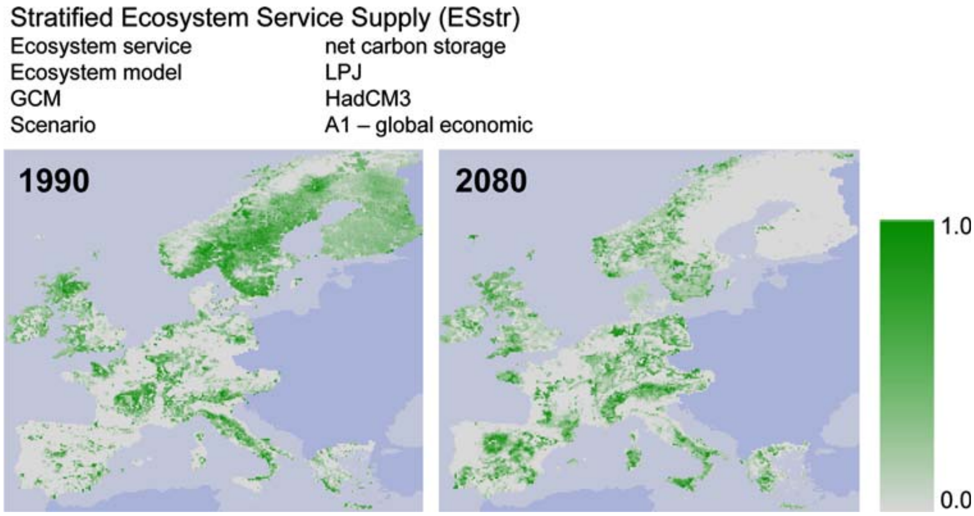

Fig. 3 The modelled net carbon storage maps are stratified by the environmental strata. Stratified ecosystem service provision maps show greater regional contrast than original, un-stratified maps because ecosystem service provision is placed in a regional instead of a continental context

Adaptive capacity index

Adaptation in general is understood as an adjustment in natural or human systems in response to actual or expected environmental change, which moderates harm or exploits beneficial opportunities. Here, adaptive capacity reflects the potential to implement planned adaptation measures and is, therefore, concerned with deliberate human attempts to adapt to or cope with change. "Autonomous adaptation" by contrast, does not constitute a conscious response (e.g. spontaneous ecological changes). The concept of adaptive capacity was introduced in the IPCC TAR (IPCC 2001), according to which the factors that determine adaptive capacity to climate change include economic wealth, technology and infrastructure, information, knowledge and skills, institutions, equity and social capital. Thus far, only one study has made an attempt at quantifying adaptive capacity based on observations of past hazard events (Yohe 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 different exposure scenarios described above. Thus a generic index was developed of macro-scale adaptive capacity. This index was based on a conceptual framework of socio-economic indicators, determinants and components of adaptive capacity, e.g. GDP per capita, female activity rate, equity, number of patents and age dependency ratio (Schröter et al. 2003; Klein et al. manuscript). The index was calculated for smaller regions (i.e. provinces and counties) and differs for each SRES storyline. The index neither includes the ability of individuals to adapt and it does not take into account the possibility that wealthy regions may be less adaptive in case of extreme disruptions in the global economy. An illustrative example of the spatially-explicit, generic adaptive capacity index over time is given in Fig. 5, for the A1 scenario. Different regions in Europe show different adaptive capacities, under this scenario, lowest adaptive capacity is expected in the Mediterranean, but the differences decline over time.

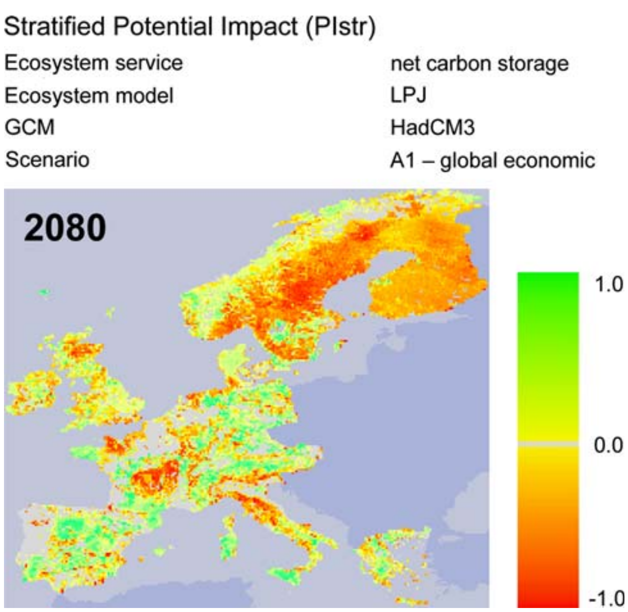

Fig. 4 The change in stratified ecosystem service provision compared to baseline conditions forms a stratified measure of the potential impact for a given location. Positive values indicate an increase of ecosystem service provision relative to environmental conditions, and therefore a positive impact, while negative impacts are the result of a decrease in ecosystem service provision compared to 1990

Vulnerability maps

The different elements of the vulnerability function (Eq. 3) have now been quantified. The last step, the combination of the stratified potential impact (PIstr) and the adaptive

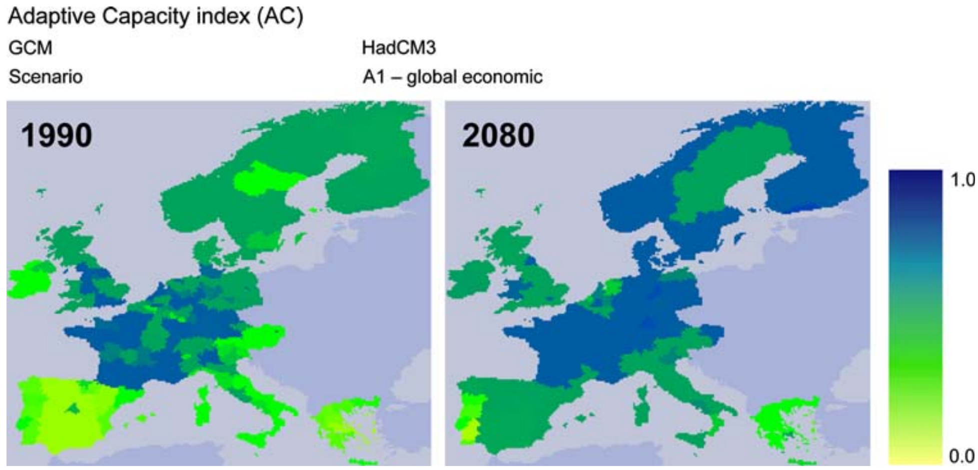

Fig. 5 Socio-economic indicators for awareness, ability and action at the regional NUTS2 (provincial) level were aggregated to a generic adaptive capacity index. Trends in the original indicators were linked to the SRES scenarios in order to map adaptive capacity in the 21st Century. For all regions adaptive capacity increases, but some regions, e.g. Portugal, remain less adaptive than others

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

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

Adaptive capacity determines colour saturation and ranges from 50 to 100% depending on the level of the AC. When the PIstr becomes more negative, a higher AC will lower the vulnerability, therefore a higher AC value has a lower saturation, resulting in a less-bright shade of red. Alternatively, when ecosystem service supply increases (PIstr > 0), a higher AC value has a higher saturation, resulting in a brighter shade of green. Conversely, in areas of negative impact, low AC gives brighter red, whereas in areas of positive impacts low AC gives less bright green. Figure 6 shows the vulnerability maps and the legend for "farmer livelihood" under the A1 scenario for the HadCM3 GCM. Under this scenario, farmer livelihood decreases in extensive agricultural areas. The role of AC becomes apparent in rural France and Spain, where France is less vulnerable than Spain due to a higher AC, i.e. a supposed higher ability of the French agricultural sector to react to these potential impacts.

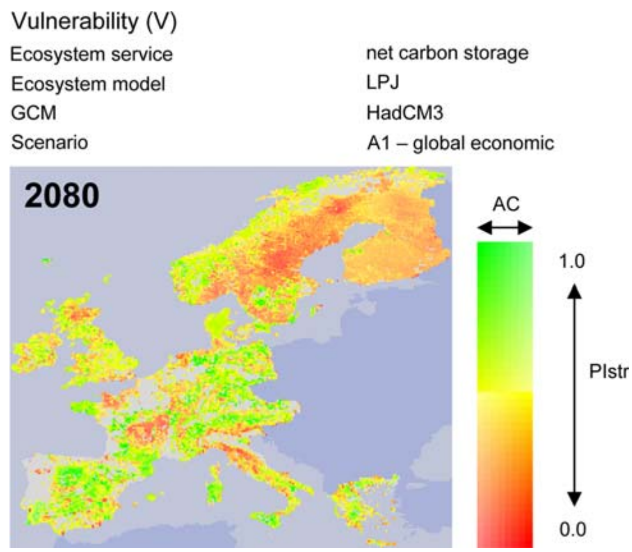

Fig. 6 Vulnerability maps combine information about stratified potential impact (PIstr) and adaptive capacity (AC), as illustrated by the legend. An increase of stratified ecosystem service provision decreases vulnerability and vice versa. At the same time vulnerability is lowered by human adaptive capacity

Selected ecosystem services

This paper aims to quantify global-change concerns for ecosystem service indicators for four sectors: agriculture, forestry, nature conservation and climate regulation (see

Table 3 Sectors, ecosystem services they rely on and indicators for these ecosystem services that were chosen together with stakeholders and ecosystem models used in ATEAM to model changes in ecosystem services, listed per sector

Sector	Service	Indicator
Agriculture	Framer livelihood	Agricultural land area
	Soil fertility maintenance	Soil organic carbon content
Forestry	Wood production	Net annual stem wood increment
	Wood supply	Net annual felling
Carbon storage	Climate protection	Net biome production, divided in net carbon storage and net carbon emission
Biodiversity and nature conservation	Beauty life support processes	

Sector	Model	Reference
Agriculture	Land use change scenarios	Rounsevell et al. 2006
	SUNDIAL	Smith et al. 1996
	ROTHC	Coleman and Jenkinson 1996; Coleman et al. 1997
Forestry	GOTILWA+	Sabaté et al. 2002
Carbon storage	LPJ (biogeochemistry)	Sitch et al. 2003; fire dynamics: Venevsky et al. 2002
Biodiversity and nature conservation	Statistical niche modelling	Araújo et al. 2002; Thuiller 2003

also Schröter et al. 2005a). These sectors rely on the sustainable supply of ecosystem services, which can therefore be used as a measure of human well being under the influence of global change threats. This is similar to the approach used by Luers et al. (2003) in looking at the vulnerability of Mexican farmers to decreasing wheat yields arising from climate damage and market fluctuations.

The ecosystem service indicators were selected in a close consultation process with stakeholders from sectors relying on these ecosystem services (see also De la Vega-Leinert et al. 2008). Schröter et al. (2005a) discuss these ecosystem service indicators in more detail. Table 3 briefly explains the indicators, which are analysed in the ATEAM vulnerability assessment. Different ecosystem modelling techniques are used for different sectors, but all ecosystem models (listed in Table 3), use the same set of internally consistent input scenarios for climate change and land-use change.

Analysis

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

To facilitate analysis of many maps created by the ATEAM project, including the scenarios, maps of ecosystem service provision and adaptive capacity, a separate software tool was developed (Metzger et al. 2004). This digital atlas offers for both the scientific community and other stakeholders access to the project's results. The ATEAM vulnerability-mapping tool generates fact sheets for each selected map, providing essential background information to help interpret the map. Furthermore, the software provides some simple analysis functionality, e.g. zooming to countries or environmental zones, simple map queries and generating scatter plots summarize multiple maps. The ATEAM vulnerability-mapping tool can be downloaded from: http://www.pik-potsdam.de/ateam/.

An effective method of analysing multiple maps is by creating scatter plots that summarise mean values of multiple maps for different regions, e.g. for different environmental zones, and the four time slices (cf Fig. 7), or maps for the four storylines summaries per environmental zone for 2080 (cf Fig. 8). Such scatter plots help to analyse differences across regions, time slices and alternative storylines. Furthermore, scatter plots can be used to analyse the variability in model outputs for different GCMs. The ATEAM vulnerability-mapping tool allows users to create such scatter plots.

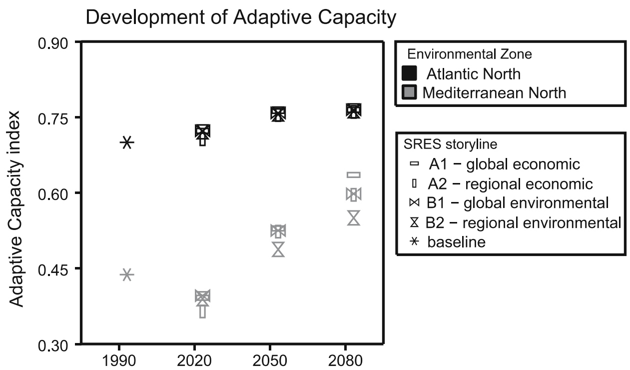

Fig. 7 Scatter plot showing the development of adaptive capacity (AC) in two environmental zones for the four SRES storylines. Although AC increases much more rapidly in the Mediterranean North than in the Atlantic North, towards the end of the 21st Century, AC is still considerable higher in the Atlantic North

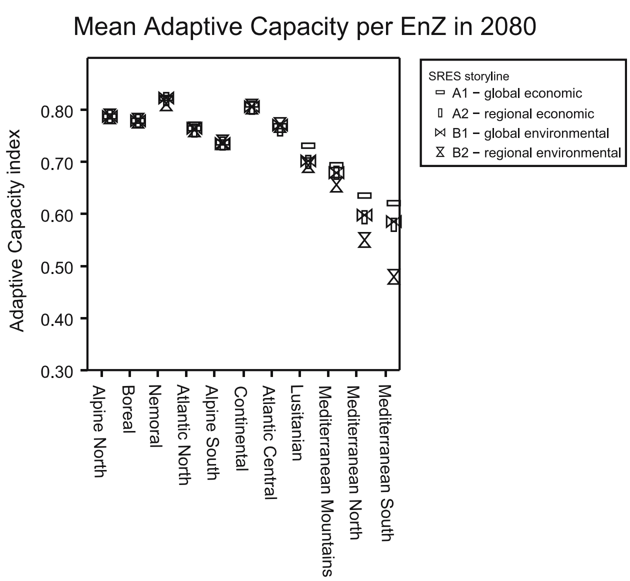

Fig. 8 Scatter plot of the mean adaptive capacity (AC) per environmental zone in 2080 for the four SRES storylines. AC in southern Europe is projected to remain lower than in northern Europe. The influence of future development pathways is greater in southern Europe than in northern Europe

Results

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

Adaptive capacity

The capacity of different countries and regions in Europe to cope with the effects of global change is projected to increase in the coming century, mainly as a result of assumed economic growth. While gross domestic product (GDP) growth is projected for all countries, countries that currently have a lower adaptive capacity (e.g. the Mediterranean countries) are most able to utilise the projected increase in wealth to substantially increase macro scale adaptive capacity (Fig. 7). In these regions, increased wealth is projected to have direct effects on the determinants of AC, such as, infrastructure, technology and equality. Countries that already show a large AC will also benefit form a growing awareness of global change impacts, but to a lesser degree, as shown in Fig. 7. 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. 8. For these countries, the development pathways associated with the scenarios have a large influence. The A1 (global-economic) scenario projects the greatest increase in AC, while the B2 (regional-environmental) scenario is associated with lower adaptive capacity.

Potential impacts

The stratified potential impacts (PIstr) are summarised per ecosystem service indicator, in a similar manner to adaptive capacity (Fig. 8). These scatter plots can now be used to (1) compare the impacts on the different ecosystem service indicators, (2) compare the impacts between regions and (3) compare the influence of the SRES storylines. A summary of these scatter plots, where PIstr is classified in five categories, is given in Table 4.

Agriculture

There are strong pressures on agricultural land use under all future scenarios, resulting in declines in agricultural production area. Therefore, PIstr for the farmer livelihood indicator, based on land availability for agriculture, is negative for most regions of Europe (Fig. 9). There appears to be a trend towards more negative PIstr for more southern environmental zones (EnZs). Especially, the Mediterranean EnZs have very negative PIstr scores. There is a strong influence of the SRES storylines on PIstr. Strong economic

Table 4 Summary of stratified potential impacts in five categories ranging from very negative to very positive change

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

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

– PIstr (lower than –15), - PIstr (between –15 and –5), 0 PIstr (between –5 and 5), + PIstr (between 5 and 15), ++ PIstr (greater than 15)

[a] PIstr for multiple indicators were averaged

[b] Different indicators were summarized separately because projected impacts show great variability between indicators

development (the A scenarios) is associated with the largest land use changes, which translates into more extreme impacts than the scenarios associated with environmentally oriented development (the B scenarios).

Soil carbon will decrease due to two factors. Firstly, climate change will speed decomposition of soil carbon and secondly, the area under agriculture will decrease. Areas that remain moist under increasing temperatures

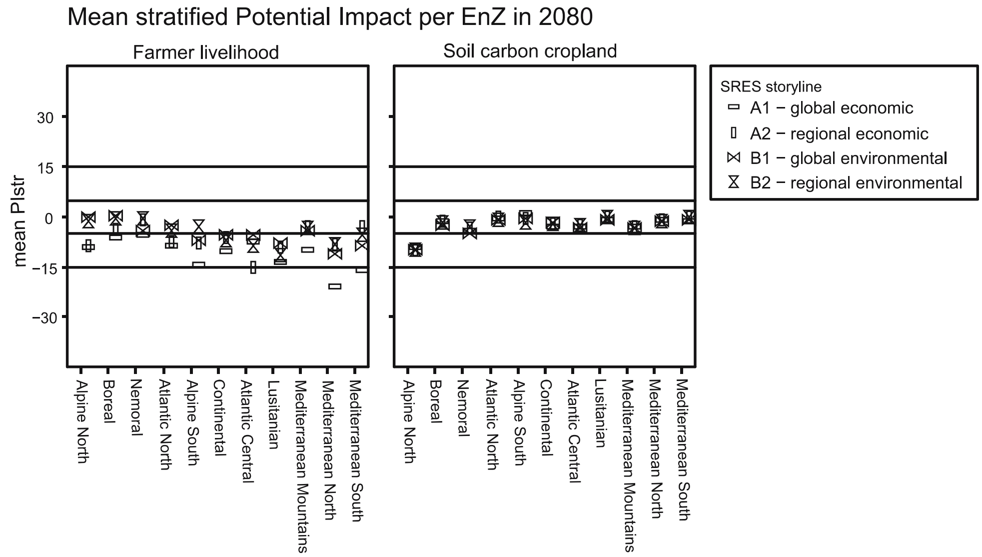

Fig. 9 Scatter plots of stratified potential impacts (PIstr) for the indicators relevant for the agriculture sector: farmer livelihood and soil carbon

(e.g. the Boreal EnZ) will lose most of the carbon, whereas in areas that become drier, soil carbon loss will be slowed. PIstr remains relatively neutral across all EnZs, except for the Boreal (Fig. 9). Furthermore, the influence of the SRES storylines is weak.

Forestry

Climate change will have an overall positive effect on forestry and therefore, on both indicators (wood production and wood supply), except in the Mediterranean, where higher temperatures and increased droughts increase tree mortality and risk of forest fire. Furthermore, except for the A2 scenario, all land use scenarios indicate an increase in forest area (Kankaanpää and Carter 2004). This will result in positive potential impacts on the ecosystem service indicators. Nevertheless, the PIstr values are relatively neutral, except for the Mediterranean, where PIstr is slightly negative (Fig. 10). This is related to increased droughts and fires. The SRES storylines do influence the results slightly. In northern Europe, the global scenarios (A) are most positive, while for southern Europe, the environmentally oriented (B) scenarios are the most positive.

Nature conservation

There are large differences in the potential impacts of global change between different groups of species. The distribution ranges of the exothermal reptiles and

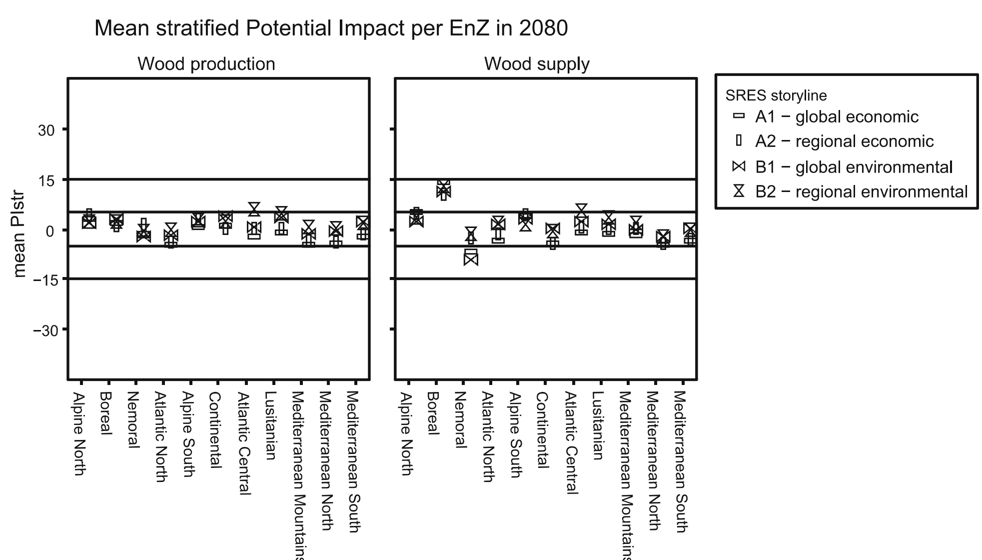

Fig. 10 Scatter plots of stratified potential impacts (PIstr) for the indicators relevant for the forestry sector: wood production and wood supply

amphibians are relatively unaffected by a warming climate. Stratified potential impact values are also relatively stable (Fig. 11). Also, for bird species, which generally have a wide climatic distribution, the projected impacts are relatively small. There are relatively positive values in the Mediterranean mountains and the Alpine South. Plant species and tree species on the other hand generally have a narrower climatic envelope. For these groups of species, the projected impacts will be the largest. An increase in biodiversity is projected for northern Europe, while southern Europe will see a strong decrease. For a large part, these changes are a direct consequence of the shifts in broad environment, since at the continental-scale biodiversity and environment are strongly correlated (see "Stratified potential impacts"). PIstr is therefore not as dramatic. Nevertheless, for plant species negative stratified potential impacts are projected for Alpine North, continental, Lusitanian, Mediterranean mountains and Mediterranean North (Fig. 11). For the tree species, PIstr is negative or very negative in most regions of Europe (Fig. 11).

Climate regulation

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

Towards the end of the 21st century, the Alpine North and Boreal are projected to become net carbon sources, while the rest of Europe becomes a net carbon sink (Zaehle et al. 2004). The negative stratified values in northern Europe and positive values elsewhere indicate that the increased sink is not just related to the shifting environments, but also to land use change, the age of the forests and management. The negative PIstr for net carbon emission in Alpine North and Boreal is an effect of the age structure of the forests in these regions. Expansion of forests, projected under all land use scenarios except A2 (contributes to the positive values in the rest of Europe. As can be seen in Fig. 12, there is a very strong difference in

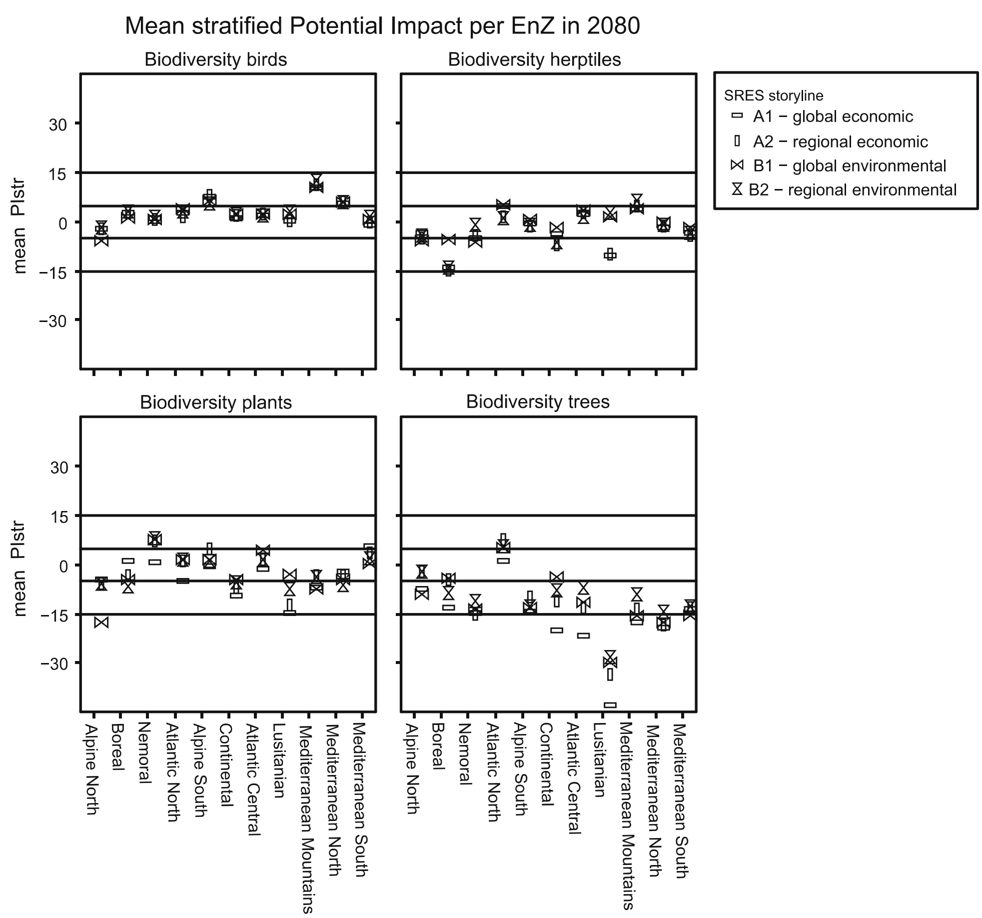

Fig. 11 Scatter plots of stratified potential impacts (PIstr) for the indicators relevant for the nature conservation sector: biodiversity of birds, reptiles and amphibians, plants and trees

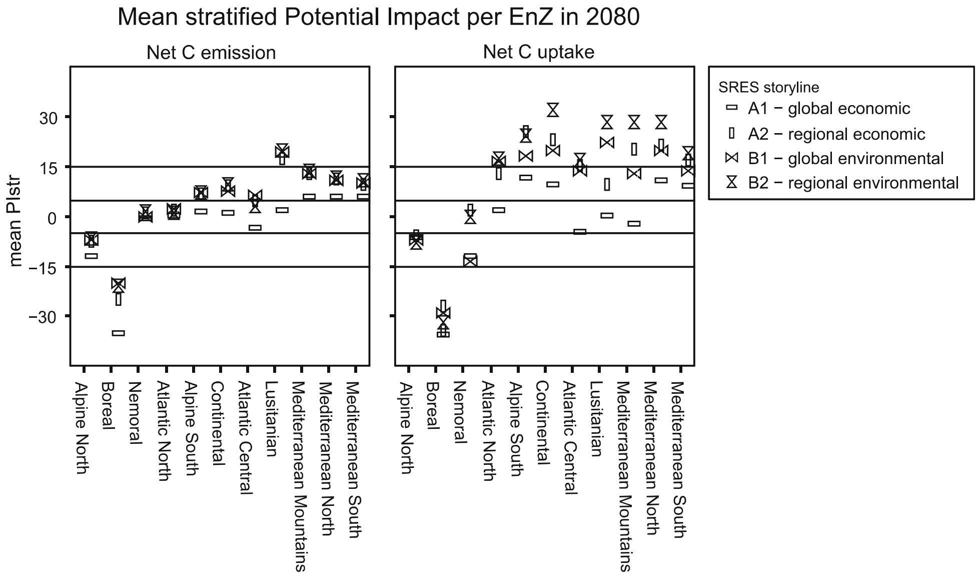

Fig. 12 Scatter plots of stratified potential impacts (PIstr) for the indicators relevant for the climate regulation sector: net carbon emission and uptake. Note that values for net carbon emission were multiplied by –1, therefore all positive values correspond to positive change and vice versa

the values of PIstr depending on the SRES storylines. The B2 scenario is associated with the largest uptake and smallest emission, while for the A1 scenario, the smallest uptake and the largest emission is projected.

Discussion and specific findings

Adaptive capacity and stratified potential impacts have been quantified and analyzed for the principal European environmental zones (in Figs. 9–12). By combining the findings from these graphs, it is possible to make some general statements about the vulnerability of people relying on ecosystem services, without quantifying the relative contributions of PIstr or AC. Firstly, this is done for each of the four sectors. Then, an attempt will be made to identify those regions, which are most vulnerable to global change, and those that are less vulnerable, and to assess the influence of the alternative development pathways.

Vulnerability per sector

Agriculture

The agricultural sector is potentially quite vulnerable to global change. While the soil carbon indicators do not give a strong signal in PIstr, in absolute terms they do tend to decrease across Europe. Farmer livelihood does give a strong PIstr signal, especially for the southern EnZs, regions that depend more heavily on agriculture than northern Europe. Also, as shown in Fig. 8, for southern European EnZs, a lower AC is indicated than for northern regions, making them especially vulnerable. In the northern EnZs (Alpine North, Boreal, Nemoral, Atlantic North), the PIstr values are only slightly negative. These regions are also projected to have a high AC under all scenarios (Fig. 8). From this, we can conclude that northern Europe is less likely to be vulnerable to projected global changes. Conversely, lower AC is indicated for southern EnZs (Lusitanian, Mediterranean zones) and PIstr reach the very negative values for farmer livelihood. Southern Europe, therefore, seems considerably more vulnerable than northern Europe.

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

Forestry

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

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

Nature conservation

Species distribution patterns are projected to change considerably. The aggregated figures presented here (Fig. 11) show that there are large differences in impacts between groups of species. But also, within the groups of species, there will be considerable differences between individual species. Furthermore, the results presented here assume full migration of the species, and do not take into account species turnover or species abundance. Nevertheless, these results do show, how there are differences in impacts between regions. Alpine North, Boreal, continental, Lusitanian and Mediterranean North and South appear to face the largest impacts. Relieving these potential impacts through an increase in adaptive capacity will not always be straightforward. However, if AC is also seen as the ability to implement more adequate reserves, ecological networks and protection programmes, perhaps the vulnerability could be reduced. For nature conservation, there does however seem to be a strong dichotomy between the development pathways and AC. Here, one would expect that the highest AC would be associated with B scenarios, where society has a higher awareness of environmental issues.

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

Climate regulation

Europe is projected to become a net source of carbon (Zaehle et al. 2004). The greatest source of carbon will be in northern Europe, due to aging forests. There is little that can be done in the sphere of additional carbon storage by forests because forests are already dominant in these regions. The rest of Europe will acts as net carbon sink. In part, this is due to a projected increase in the area under forestry (Kankaanpää and Carter 2004). In addition, climate change will be beneficial for forest productivity in most regions. However, an increased risk of forest fire could reduce this potential sink (Schröter et al. 2005a). While sustainable intensive management could help retain stored carbon, there is only limited scope for further carbon storage to counteract emissions.

Northern Europe is projected to be vulnerable with respect to climate regulation, while other parts of Europe show an increased capacity for carbon storage. Adaptation measures will not be able to prevent Europe from becoming a net source of carbon.

Vulnerability across Europe

As can be seen clearly from the summarising Table 4, projected impacts from global changes vary greatly between sectors. Agriculture faces, relatively negative prospects for forestry impacts, will be relatively neutral, and for the indicators for climate regulation impacts will be positive in southern Europe, but negative in northern Europe. For biodiversity, projected impacts vary greatly between groups of species. Nevertheless, there are also notable differences between regions of Europe.

Table 4 shows that Alpine North and the Boreal have the most negative PIstr scores across the sectors. However, because these regions also have the highest projected AC, and in these regions agriculture is less important than in most other parts of Europe, the overall vulnerability will not be as great as it may seem at first.

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

Finally, the Mediterranean region is projected to have the lowest AC, as well as large negative impacts for agriculture and biodiversity (Table 4), and to a lesser extent forestry, as discussed previously. The Mediterranean mountains are less vulnerable than the other Mediterranean zones.

Influence of development pathways

As Figs. 8–12 and Table 4 show, in many cases, the different development pathways embodied by the SRES storylines will influence the eventual vulnerability. Table 4 shows that for the sectors agriculture, forestry and climate regulation, in combination, the A1 scenario has the most negative scores (relatively more negative impacts than positive impacts), A2 and B1 scores are more or less neutral, and the scores for B2 are slightly positive. However, there are differences between sectors and making specific statements about the preferred development pathways is a political matter outside the scope of this paper.

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

Assumptions and uncertainties

Studies concerned with future developments are necessarily based on many assumptions and clouded by uncertainty. These uncertainties are complex and difficult to generalize or indicate with each map. It is nevertheless important to recognize this, making assumptions explicit and discussing uncertainties. For the present study, three categories of assumptions can be discerned: (1) those associated with the SRES storylines and scenarios, (2) those associated with the ecosystem models used to estimate ecosystem service provision 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. (2006). For the projections of ecosystem services, uncertainties and assumptions are discussed by Schröter et al. (2005a) and in the individual publications of the various models, listed in Table 3.

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. 2005b; Metzger et al. 2008) is based on the ATEAM climate change scenarios. Some additional uncertainty is added by the statistical classification, as discussed by Metzger et al. (2005b). 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.

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

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

Limitations of the approach

As indicated previously, there is a demand for methods to integrate multidisciplinary assessments and to incorporate measures of adaptive capacity (IPCC 2001; Kasperson 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. In the present approach, this processing comprised three parts: (1) the stratification of the ecosystem service maps adds considerable conceptual complexity, but is of importance for allowing comparison across the European environment. Whilst both the environmental stratification that was used (Metzger et al. 2005b) and the reference value (ESref) are essentially arbitrary, they can be applied consistently to different ecosystem service indicators and scenarios, (2) the adaptive capacity index forms the weakest part of the assessment, but meets the needs for a macro-scale indicator. Arguably separate indicators should be developed for different sectors or ecosystem services and (3) the visual combination of the two indices results in an intuitive map, but also includes a bias, especially in the scaling of the adaptive capacity index (saturation). The relative contribution of AC can be manipulated by changing the scaling. As the approach is applied, more advanced methods of combining stratified potential impact (PIstr) and adaptive capacity (AC) may be developed, i.e. through fuzzy logic or qualitative differential equations. However, a prerequisite for this is the further understanding of how PIstr and AC interact and influence vulnerability.

Concluding remark

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

Acknowledgments The work was carried out as part of the EU funded Fifth Framework project ATEAM (Advanced Terrestrial Ecosystem Assessment and Modelling, Project No. EVK2-2000-00075). Many members in the consortium contributed to the discussions that helped shape the work in this paper.

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