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Towards a spatially explicit and quantitative vulnerability assessment of environmental change in Europe

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Abstract Over the next century, society will increasingly be confronted with the impacts of global change (e.g. pollution, land use changes, and climate change). Multiple scenarios provide us with a range of possible changes in socio-economic trends, land uses and climate (i.e. exposure) and allow us to assess the response of ecosystems and changes in the services they provide (i.e. potential impacts). Since vulnerability to global change is less when society is able to adapt, it is important to provide decision makers with tools that will allow them to assess and compare the vulnerability of different sectors and regions to global change, taking into account exposure and sensitivity, as well as adaptive capacity. This paper presents a method that allows quantitative spatial analyses of the vulnerability of the human-environment system on a European scale. It is a first step towards providing stakeholders and policy makers with a spatially explicit portfolio of comparable projections of ecosystem services, providing a basis for discussion on the sustainable management of Europe's natural resources.

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Introduction

Even if human society is very successful in entering a sustainable development pathway, significant global changes are likely to occur within this century. The atmospheric carbon dioxide concentration could double be compared to pre industrial concentrations, while the global average surface temperature is projected to increase by 1.4–5.8°C by 2100 (IPCC 2001a). Land use changes will have an immediate and strong effect on agriculture, forestry, rural communities, biodiversity and amenities such as traditional landscapes (UNEP 2002; Watson et al. 2000). In the face of these changes, the question posed by Kates et al. (2001) of ''How to integrate or extend today's operational systems for monitoring and reporting on environmental and social conditions to provide more useful guidance for efforts to navigate a transition towards sustainability?'' poses a major challenge to science. Vulnerability assessments aim to inform the decision-making of specific stakeholders about options for responding and adapting to the effects of global change (Schröter et al. 2005a). The large potential, but still early stage of development, of spatially referenced modelling and GIS mapping methods for vulnerability assessment has been recognised (Kasperson and Kasperson 2001). This paper describes an approach based on such spatially explicit methods developed to assess where in Europe people may be vulnerable to the loss of particular ecosystem services, associated with the combined effects of both climate and

land use change. This approach was developed as part of the ATEAM project [Advanced Terrestrial Ecosystem Analysis and Modelling, Schröter et al. (2005b), http://www.pik-potsdam.de/ateam].

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

In the vulnerability approach presented here, the provision of ecosystem services is used as an approximate measure of human well-being adversely impacted by global change stressors, similar to the approach suggested by Luers et al. (2003). More information about the sectors and ecosystem services analysed in the ATEAM project can be found in Schröter et al. (2005b).

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

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

The vulnerability concept introduced here is based on this definition and was developed to integrate results from a broad range of different, spatially explicit models. Projections of changing ecosystem service provision and changing adaptive capacity are integrated into spatially explicit maps of vulnerability for different human sectors. Such vulnerability maps provide a means for making comparisons between ecosystem services, sectors, scenarios and regions to tackle multidisciplinary questions such as:

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

The term vulnerability is defined in such a way that it includes both the traditional elements of an impact assessment (i.e. sensitivities of a system to exposures), and adaptive capacity to cope with potential impacts (PIs) of global change (Schröter et al. 2005a; Turner et al. 2003). To ensure the relevance of the vulnerability maps, stakeholders were consulted at specific points throughout the project.

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

The vulnerability approach

Towards a quantification of vulnerability

The IPCC definitions of vulnerability to climate change, and related terms such as exposure, sensitivity, and adaptive capacity, form a suitable starting position to explore possibilities for quantification of vulnerability. However, because vulnerability assessments consider not only climate change, but also other possible stressors such as land use change (Turner et al. 2003), some of the IPCC definitions were modified somewhat. Furthermore, we adjusted the definition of vulnerability so that it is more directly related to the human-environment system.[1] In this paper, we assess the vulnerability of human sectors, relying on ecosystem services:

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

Vulnerability is the degree to which an ecosystem service is sensitive to global change plus the degree to which the sector that relies on this service is unable to adapt to the changes.

Table 1 lists the definitions of fundamental terms used in this paper and gives an example of how these terms could relate to the carbon storage sector. From these definitions the following generic functions are constructed, describing the vulnerability of a sector relying on a particular ecosystem service in an area under a certain scenario at a certain point in time. Vulnerability is a function of exposure, sensitivity and adaptive capacity (Eq. 1). PIs are a function of just exposure and sensitivity (Eq. 2). Therefore, vulnerability is a function of PIs and adaptive capacity (Eq. 3):

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

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

$$V(es, x, s, t) = f(E(es, x, s, t), AC(es, x, s, t)), \quad (3)$$

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

These simple conceptual functions describe how the different elements of vulnerability are related to each other. Nevertheless, they are not operational for converting model results into vulnerability maps. Operationalising these functions requires various tools and several steps, which we describe in detail below. An overview of the steps involved in the vulnerability assessment is depicted in Fig. 1. Using global change scenarios as input data, ecosystem services and a generic adaptive capacity index are modelled spatially for three time slices and baseline conditions (ecosystem services at 10 arcmin × 10 arcmin resolution; adaptive capacity index at province level). The indicators are then combined to produce vulnerability maps. Stakeholder dialogue and close involvement of different scientific disciplines help ensure relevance of results.
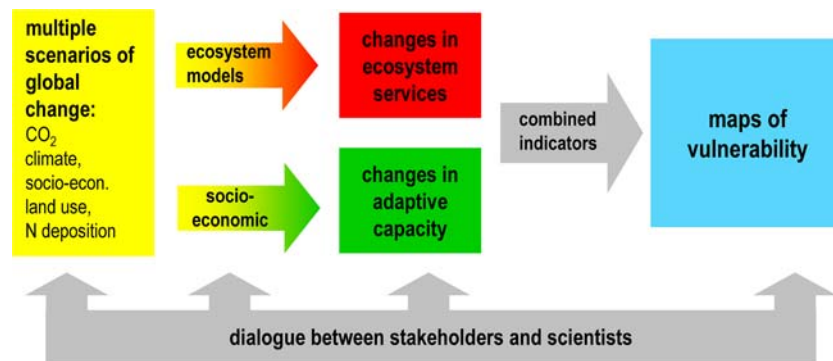
This vulnerability framework facilitates integrated analyses and comparisons between the multitude of maps of ecosystem services, and between sectors,

Table 1 Definitions of important terminology 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	Ecosystem models	Changes in local management, change in tree species
Potential impact (PI)	All impacts that may occur given projected environmental change, without considering planned adaptation	Ecosystem models	Increase in storage
Adaptive capacity (AC)	The potential to implement planned adaptation measures	Vulnerability assessment	Capacity to implement better fire management
Vulnerability (V)	The degree to which an ecosystem service is sensitive to global change plus the degree to which the sector that relies on this service is unable to adapt to the changes	Vulnerability assessment	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	The future will tell	Carbon loss to forest fires

IPCC TAR Intergovernmental Panel on Climate Change Third Assessment Report (IPCC 2001c)

Fig. 1 Schematic overview of the ATEAM vulnerability assessment framework. The basic elements are as follows: multiple scenarios of global change, translation into impacts and adaptive capacity changes, combination into vulnerability maps, continuous stakeholder dialogue

scenarios, regions and points in time (time slices). Several examples of possible questions that a vulnerability framework could help answer were listed in the introduction. The framework is designed to produce maps that are intuitive to users outside the scientific community. In the next section, the vulnerability framework is explained by an example. The full set of maps produced by the ATEAM project is available on a CD-ROM (Metzger et al. 2004, can be downloaded at http://www.pik-potsdam.de/ateam).

Creating a vulnerability map—an example

The full vulnerability assessment of the ATEAM project includes all ecosystem services that were examined in the project (Metzger et al. 2004; Metzger 2005). In this paper, we focus on the ecosystem service climate protection, and its indicator carbon storage [net biome exchange (NBE)] as an example to present the ATEAM methodology for mapping and analysing vulnerability. The following sections elaborate on, and quantify, the elements of the vulnerability functions for net carbon storage under one scenario and one Global Climate Model (GCM), resulting in vulnerability maps for people interested in climate protection.

Exposure

For global change research, the IPCC recommends to use a family of future scenarios that captures the range of uncertainties associated with driving forces and emissions, without assigning probabilities or likelihood to any individual scenario (Nakicenovic et al. 2000; Carter et al. 2001). Our study is therefore based on multiple quantitative scenarios of global change, which are derived from the A1fi, A2, B1 and B2 scenarios developed for the IPCC Special Report of Emission Scenarios (SRES) (Nakicenovic et al. 2000). In summary, exposure in our study is represented by a consistent set of spatially explicit scenarios (10 arcmin × 10 arcmin resolution for the 15 European Union countries plus Norway and

Switzerland) of the main global change drivers, i.e. socio-economic variables, atmospheric carbon dioxide concentration, climate, and land use for three time slices (2020, 2050, 2080) and baseline conditions (1990). By using multiple scenarios, the vulnerability assessment spans a wide range of possible futures. This enables us to differentiate regions that are vulnerable under most scenarios, regions that are vulnerable under specific scenarios and regions that are not vulnerable under any scenario.

To obtain climate projections, different GCMs have been run for the greenhouse gas (GHG) emission scenarios and the results are available through the IPCC data distribution centre. For our study, climate change scenarios from four state-of-the-art GCMs (HadCM3, CSRIO2, CGCM2 and PCM) were downscaled to a 10 arcmin × 10 arcmin resolution by anomilsing the GCM information relative to the 1961–1990 observed climatology (Mitchell et al. 2004). The scenarios were anomalised relative to the observed climatology from 1961–1990 to produce information about future European climates at a spatial resolution that would not have been possible using models alone. There is general agreement among the different GCMs in the trends of temperatures change. In comparison, HadCM3 predicts the greatest changes, and PCM is the most modest. Change in precipitation shows greater variability as well as disagreement in regional trends (Ruosteenoja et al. 2003). The 16 alternative future climates (4 scenarios × 4 GCMs) represent 93% of the range of possible global warming presented by the IPCC (2001c).

A coherent set of future land use scenarios was developed based on an interpretation of the global storylines of the SRES storylines for the European region (Rounsevell et al. 2005, 2006; Ewert et al. 2005; Kankaanpää and Carter 2004). Rounsevell et al. (2006) give a comprehensive summary of the dataset. Aggregate totals of land use change were estimated. For instance, data on the demand for food, biomass energy crops, forest products and urban areas were derived from the IMAGE model (IMAGE team 2001), and

allocated using spatially explicit rules, incorporating scenario specific assumptions about policy regulations. Changes in agricultural land use were calculated from food demand considering effects on food production of climate change, increasing CO_2 concentration, and technological development (Ewert et al. 2005). A hierarchy of importance of different land use types was introduced to account for competition between land use types and to assign the relative coverage of 14 main land use types to each 10 arcmin × 10 arcmin grid cell (Rounsevell et al. 2006). The scenario changes are most striking for the agricultural land uses, with large area declines resulting from assumptions about future crop yield development with respect to changes in the demand for agricultural commodities. Abandoned agricultural land is a consequence of these assumptions. Increases in urban areas (arising from population and economic change) are similar for each scenario, but the spatial patterns are very different. This reflects alternative assumptions about urban development processes. Forest land areas increase in all scenarios, although such changes will occur slowly and largely reflect assumed policy objectives. The scenarios also consider changes in protected areas (for conservation or recreation goals) and how these might provide a break on future land use change. The approach to estimate new protected areas is based in part on the use of projections of species distribution and richness. All scenarios assume some increases in the area of bioenergy crops with some scenarios assuming a major development of this new land use.

Ecosystem service provision and potential impact

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

Figure 2 shows the results of the first step towards mapping PIs on the carbon sector—the ecosystem service carbon storage, as modelled by the dynamic global vegetation model LPJ (Sitch et al. 2003), under a specific climate and land use scenario (A2—regional economic, HadCM3 GCM).

Stratified ecosystem service provision and the stratified potential impact index

Maps of PI, defined in the previous section as the change in ecosystem service provision compared to baseline conditions, are valuable for analysing impacts in a certain region. However, because ecosystem services tend to be highly correlated with environmental factors, they do not allow for comparisons across the European environment. Inherently, some environments have high values for particular ecosystem services whereas other regions have lower values. For instance, Spain has high biodiversity [5,048 vascular plant species (WCMC 1992)], but low grain yields [2.7 t ha^{-1} for 1998–2000 average (Ekboir 2002)], whereas The Netherlands have a far lower

Fig. 2 Net carbon storage across Europe as modelled by the LPJ model for the A2 scenario and the HadCM3 GCM for climate and land use change. Grey areas are net sources of carbon. Carbon emission is not mapped here because in the vulnerability framework introduced here, ecosystem services and antagonist disservices cannot me mapped together
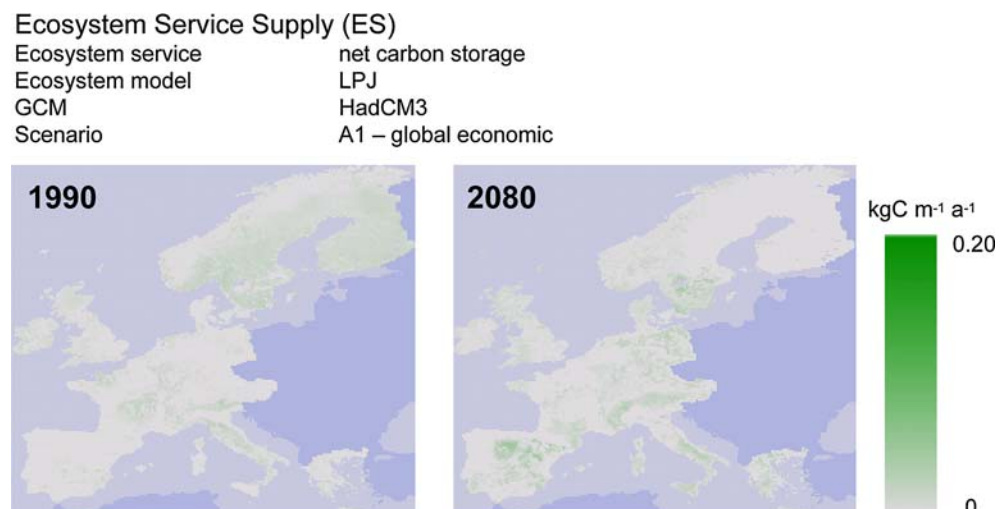

Ecosystem Service Supply (ES)

Ecosystem service	net carbon storage
Ecosystem model	LPJ
GCM	HadCM3
Scenario	A1 – global economic

1990   2080

kgC m^{-1} a^{-1}

0.20

0

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 (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**

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 PIs; in this example, it is always –20%. When changes are stratified by their environment, comparison of PIs in their specific environmental context is possible. The ''stratified PI'' 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 the text). Note that in grid cell B, PIstr id 0.0 even though ES decreases because relative to the environmental condition, ecosystem service provision is constant (see the text)

biodiversity [1,477 vascular plant species (van der Meijden et al. 1996)], but a very high grain yield (8.1 t ha^{-1} for 1998–2000 average (Ekboir 2002)). Therefore, while providing useful information about the stock of resources at a European scale, absolute differences in species numbers or grain yield levels are less useful measures for comparing regional impacts between these countries. A relative change would overcome this problem (e.g. –40% grain yield in Spain vs. +8% in The Netherlands), but also has a serious limitation: the same relative change can occur in very different situations. Table 2 illustrates how a relative change of –20% can represent very different impacts, both between and within environments. Therefore, comparisons of relative changes in single grid cells must also be interpreted with great care and cannot easily be compared.

For a meaningful comparison of grid cells across Europe, it is necessary to place values of ecosystem service provision in their regional environmental context, i.e. in an environmental envelope, or stratum, that is suited as a reference for the values in an individual grid cell. Because environments will alter under global change, consistent environmental strata must be determined for each time slice. We used the recently developed Environmental Stratification of Europe (EnS) to stratify the modelled ecosystem services (Metzger et al. 2005a; Jongman et al. 2006).

The EnS was created by statistical clustering of selected climatic and topographic variables into 84 strata and 13 aggregated Environmental Zones (EnZ). A detailed description of the creation of this dataset is given by Metzger et al. (2005a). The individual strata represent regions with relatively homogenous climatic conditions. Because at a European scale environmental characteristics (e.g. soil, vegetation, land use, species) are determined by climate (Walter 1973; Klijn and de Haes 1994; Metzger et al. 2005a) they are referred to as environmental strata. Examples of some of the 84 environmental strata are the nemoral strata in southern Sweden, two upland strata in the United Kingdom, several alpine strata and a separate stratum for the extreme environment around Almeria in southern Spain. For summary purposes, the individual strata have been aggregated into 13 EnZs. This aggregation (?) is based on cut-off levels in the mean first principal component score of the clustering variables for each stratum (Metzger et al. 2005a). Detailed descriptions of the individual strata and the EnZs can be found in Shkaruba et al. (2006). The EnS was constructed using tried-and-tested statistical procedures (Bunce et al. 1996; Metzger et al. 2005a) and shows significant correlations with principal European ecological datasets (Metzger et al. 2005a). Furthermore, Kappa values for a comparison between the EnS and other European classifications indicate 'good' or 'very good' agreement (Metzger et al. 2005a, b).

For each stratum, a discriminant function was calculated for the variables available from the climate change scenarios described above (see Exposure). With these functions, the 84 climate strata were mapped for the different GCMs (4), SRES storylines (4) and time slices (3), resulting in 48 maps of shifted climate strata. These maps were used to place the modelled ecosystem service values in their environmental context consistently. Maps of the EnS, for baseline and the HadCM3–A2 scenario are mapped in Fig. 3 for 13 aggregated EnZs.
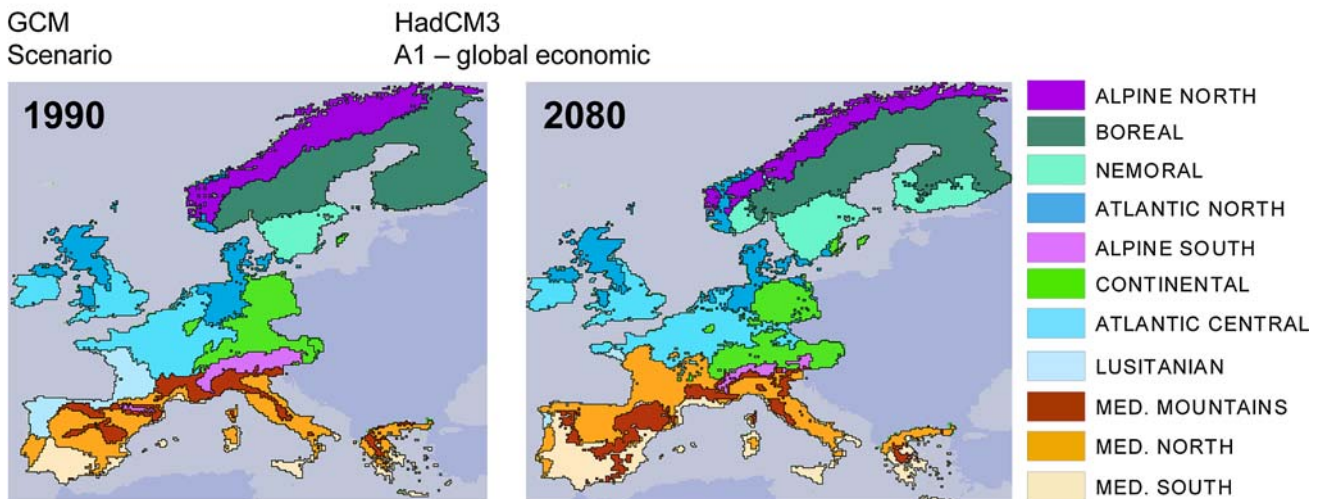
Shifting stratification

Fig. 3 Climatic and topographic variables were statistically clustered into 84 environmental classes. By calculating discriminant functions for the classes they can be mapped for each global change scenario, resulting in maps of shifting climate classes that can be used for stratification. For presentation purposes, here the classes are aggregated to Environmental Zones. *ALN* Alpine North, *BOR* Boreal, *NEM* Nemoral, *ATN* Atlantic North, *ALS* Alpine South, *CON* Continental, *LUS* Lusitanian, *MDM* Mediterranean Mountains, *MDN* Mediterranean North, *MDS* Mediterranean South

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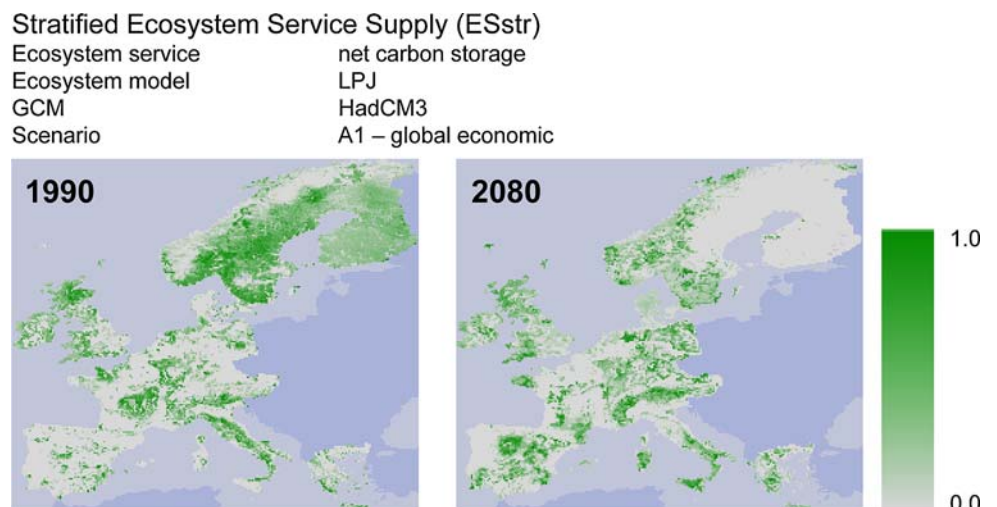
$$\mathrm{ESstr}(\mathrm{es},x,s,t) = \mathrm{ES}(\mathrm{es},x,s,t)/\mathrm{ESref}(\mathrm{es},\mathrm{ens},x,s,t),$$

$$(4)$$

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

We thus create a map in which ecosystem services are stratified by a static definition of their environment and expressed relative to a reference value (Fig. 4).

Fig. 4 The modelled net carbon storage maps are stratified by the environmental strata. Stratified ecosystem service provision maps that show greater regional contrast than original, un-stratified maps because ecosystem service provision is placed in a regional instead of a continental context

Because the environment changes over time, for a given location the environmental reference may change. Therefore, both the reference value and the environmental stratification are determined for each time slice. As shown in Fig. 4, the stratified ecosystem service map shows more regional detail than the original ecosystem service map. This is the detail required to compare PIs across regions (see also Table 2).

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

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

where PIstr is the stratified PI, ESstr is the stratified ecosystem service provision, es is the ecosystem service, x a grid cell, s a scenario, t a time slice.

PIstr is a function of both changing ecosystem service provision and the changing environmental conditions (climate). It is important to understand that PIstr does not necessaril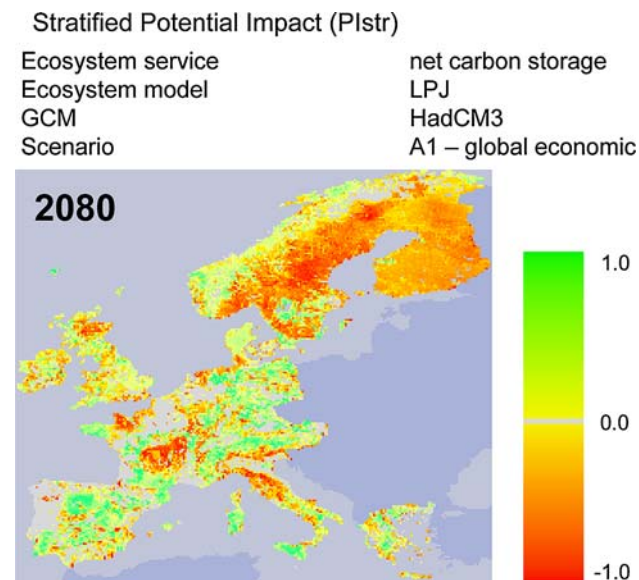y follow the same trend as the PI, the absolute change in ecosystem service provision. If environmental conditions become less favourable for a certain ecosystem service, a certain level of decrease in ecosystem service provision would be expected, purely on this basis. When the old level of ecosystem service provision is maintained, PIstr will be positive: the ecosystem service provision relative to environmental conditions is greater than before. In Table 2, grid cell B of environment 1 has a PIstr of 0.0, because both the ecosystem service provision (ES) and ESref show a similar decrease (ES decreases by 0.2, ESref by 0.3). In the same manner, PIstr can be negative, even when in absolute terms ecosystem service provision increases. In such cases, the environmental conditions become more favourable for the ecosystem service, but these more favourable conditions are not utilised. When interpreting maps of changing PIs (e.g. Fig. 5) or vulnerability, it is important to keep such possibilities in mind. In order to fully interpret the vulnerability of a region it is important to look not only at the vulnerability maps, but also at the constituting indictors separately.

Adaptation

Adaptation is any adjustment in natural or human systems to a changing environment (IPCC 2001b; Table 2). Adaptation can be autonomous or planned. Autonomous adaptation is "triggered by ecological changes in natural systems and by market or welfare changes in human systems, but does not constitute a conscious response to environmental change" (IPCC 2001b). Autonomous adaptation changes sensitivity by changing a system's state. In other words, it is part of the internal feedbacks in the human-environment system and its subsystems like ecosystems and markets, such as when forest tree species extent their bioclimatic range due to evolutionary adaptation, or the slowing of demand after price increase resulting from supply shortages. However, ecosystem models are currently hardly able to represent such system state changes, i.e. they do not dynamically model adaptive feedbacks in a coupled way (Smith et al. 1998).

Adaptation also comprises planned adaptation. Planned adaptation can take place locally, as adaptive management decisions by individuals or small planning groups, such as planting a drought resistant crop type. Furthermore, planned adaptation can be implemented on a larger or macro-scale by communities and regional representatives, such as establishing flood plains to buffer seasonal river-runoff peaks. In this study, we distinguish local scale adaptation and macro-scale adaptation, with the awareness that this separation is not always clear. Local scale adaptation is captured in

Stratified Potential Impact (PIstr)

Ecosystem service	net carbon storage
Ecosystem model	LPJ
GCM	HadCM3
Scenario	A1 – global economic

Fig. 5 The change in stratified ecosystem service provision compared to baseline conditions forms a stratified measure of the potential impact (PI) 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

the ecosystem models by taking into account local management e.g. in agriculture, forestry and carbon storage. Macro-scale adaptation enters our assessment in two ways. Broad overarching management choices based on the SRES storylines are incorporated in to the land use scenarios (Rounsevell et al. 2005, 2006) via the IMAGE model (IMAGE team 2001), which considers the impacts of climate change and CO_2 concentration on, e.g. crop yields and markets. Secondly, the capacity of regions for macro-scale adaptation is considered by a generic adaptive capacity index. This adaptive capacity is enters the vulnerability assessment directly, and is described in the next section.

Adaptive capacity index

To capture society's ability to implement planned adaptation measures, the ATEAM project developed a generic index of macro-scale adaptive capacity. This index is based on a conceptual framework of socio-economic indicators, determinants and components of adaptive capacity, e.g. GDP per capita, female activity rate, income inequality, number of patents, and age dependency ratio (Schröter et al. 2003). The approach will be described in detail in Klein et al. (manuscript). Adaptation in general is understood as an adjustment in natural or human systems in response to actual or expected environmental change, which moderates harm or exploits beneficial opportunities. In our study, adaptive capacity reflects the potential to implement planned adaptation measures and is therefore concerned with deliberate human attempts to adapt to or cope with change, and not with autonomous adaptation (see above). The concept of adaptive capacity was introduced in the IPCC TAR (IPCC 2001b). According to the IPCC TAR, factors that determine adaptive capacity to climate change include economic wealth,

technology and infrastructure, information, knowledge and skills, institutions, equity and social capital. So far, only one paper has made an attempt at quantifying adaptive capacity based on observations of past hazard events (Yohe and Tol 2002). For our vulnerability assessment framework, we sought present-day and future estimates of adaptive capacity that would be quantitative, spatially explicit and based on, as well as consistent with, the exposure scenarios described above. The index of adaptive capacity we developed to meet these needs is an index of the macro-scale outer boundaries of the capacity of a region (i.e. provinces and counties) to cope with changes. The index does not include individual abilities to adapt. An illustrative example of our spatially explicit generic adaptive capacity index over time is shown in Fig. 6, for a particular scenario (A2). Note that adaptive capacity is a function of socio-economic characteristics and is therefore also specific for each SRES scenario. Different regions in Europe show different macro-scale adaptive capacity—under this scenario, lowest adaptive capacity is expected in the Mediterranean and improves over time but large regional differences remain.

Vulnerability maps

The different elements of the vulnerability function (Eq. 3) have now been quantified, as summarised in Fig. 7. The last step, the combination of the stratified PI index (PIstr) and the adaptive capacity index (AC), is however the most questionable step, especially when taking into account the limited understanding of adaptive capacity. We therefore decided to create a visual combination of PIstr and AC without quantifying their intrinsic relationship. The vulnerability maps will therefore just rank the vul-

Fig. 6 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 twenty-first century. For all regions adaptive capacity increases, but some regions, e.g. Portugal, remain less adaptive than others
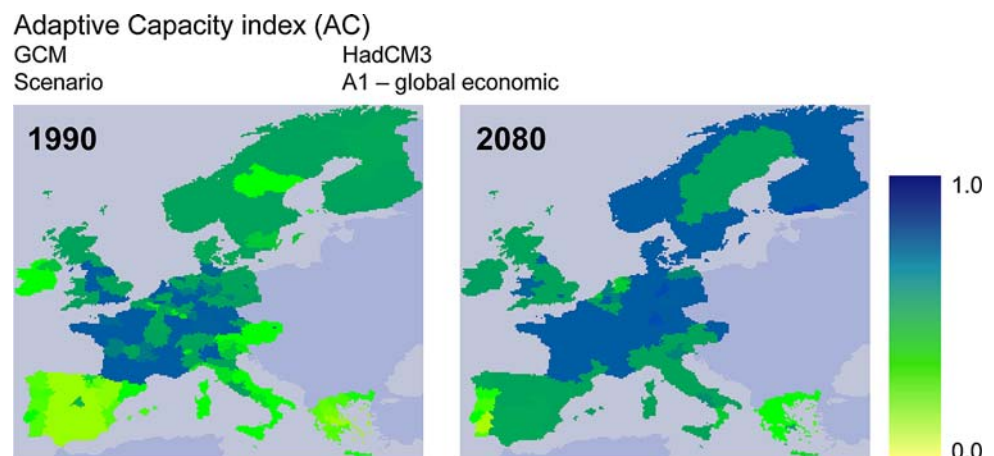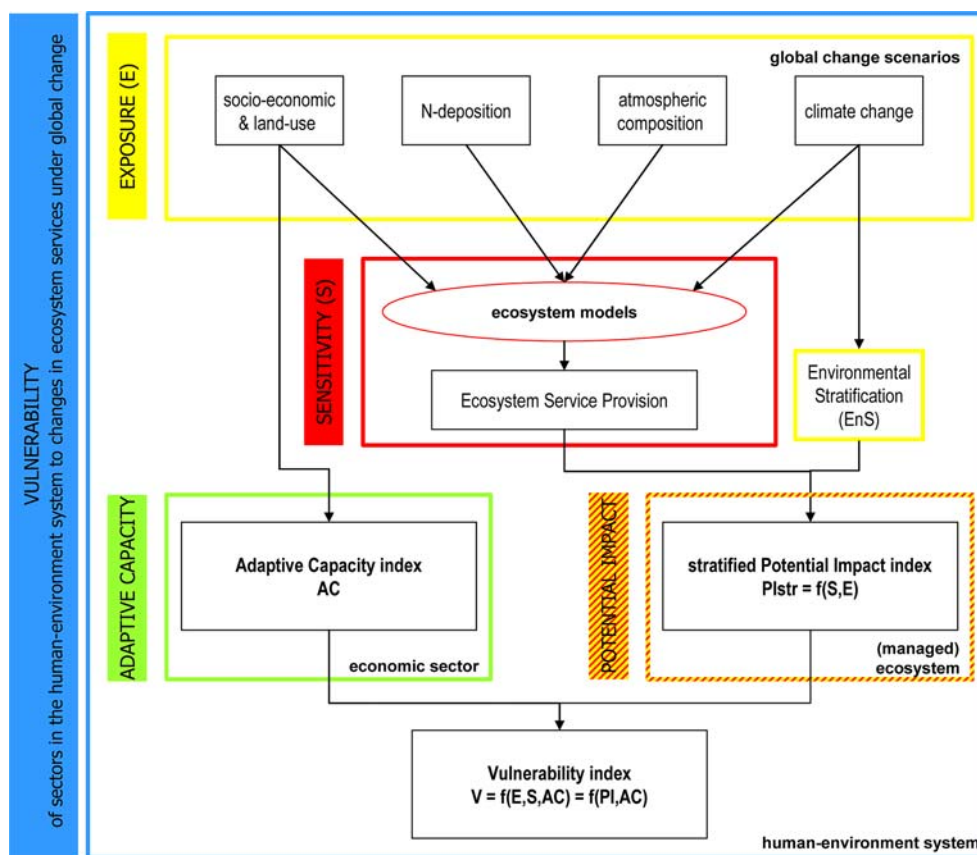
Fig. 7 Summary of the ATEAM approach to quantify vulnerability. Global change scenarios of exposure are the drivers of a suite of ecosystem models that make projections for future ecosystem services provision for a 10 arcmin × 10 arcmin spatial grid of Europe. The social-economic scenarios are used to 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 PI of a given location. The stratified PI and adaptive capacity indices can be combined, at least visually, to create European maps of regional vulnerability to changes in ecosystem service provision

nerability of areas and sectors. For further analytical purposes the constituents of vulnerability, the stratified PI index and the adaptive capacity index, must be viewed separately.

Trends in vulnerability follow the trend in PI: when ecosystem service provision decreases, humans relying on that particular ecosystem service become more vulnerable in that region. Alternatively, when ecosystem service provision increases, vulnerability decreases. Adaptive capacity can lower vulnerability considerably but not eliminate it completely. In regions with similar PIstr, the region with a high AC will be less vulnerable than the region with a low AC. The PIstr index determined the Hue, ranging from red (decreasing stratified ecosystem service provision, PIstr = –1, highest negative PI) via yellow (no change in ecosystem service provision, PIstr = 0, no PI) to green (increase in stratified ecosystem service provision, PIstr = 1, highest positive PI). The adaptive capacity index (AC) determines the colour saturation, ranging from 50 to 100% depending on the level of the AC. When the PIstr becomes more negative, a higher AC will lower the vulnerability, therefore a higher AC value gets a lower saturation, resulting in a less bright

shade of red. Alternatively, when ecosystem service provision increases (PIstr > 0), a higher AC value will get a higher saturation, resulting in a brighter shade of green. Inversely, in areas of negative impact, low AC gives brighter red, whereas in areas of positive impacts low AC gives less bright green. Figure 8 shows the vulnerability maps and the legend for carbon storage under the A2 scenario for the HadCM3 GCM. Under this scenario carbon storage will increase in large areas of Europe. A few regions, most notably the Boreal, parts of Scotland and the Massif Central, France, become a net source of carbon. The role of AC is apparent in the Boreal, where Finland is less vulnerable than Sweden due to a slightly higher AC, i.e. a supposed higher ability of Finland to react to these changes.

Analysis of vulnerability maps

Spatially modelling ecosystem services shows that global changes will impact ecosystems and humans differently across Europe. However, visual interpretation of detailed spatial patterns in maps is difficult and relies on personal judgement and experience.
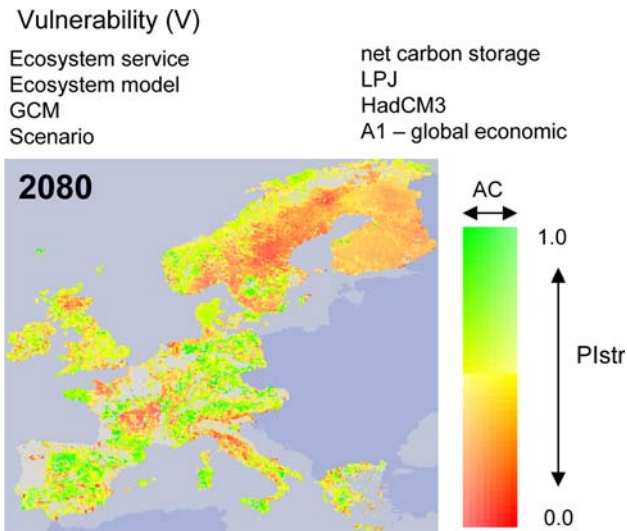
Fig. 8 Vulnerability maps combine information about stratified PI (*PIstr*) and adaptive capacity (*AC*), as illustrated by the legend. An increase of stratified ecosystem service provision decreases vulnerability and visa versa. At the same time, vulnerability is lowered by human adaptive capacity

A multitude of maps (scenarios, time slices, GCMs) further complicates visual analysis of the maps. To make results more accessible, both to stakeholders and scientists, many of the analyses can take place in summarised form. For instance, changes can be summarised per (current) EnZ or per country. Figure 9 gives an example of a summary of the changes in PIstr in 2080 for the EnZs, showing the variability between SRES storylines and GCMs. Similar graphs can be made for the other components of vulnerability, which can also be analysed separately.

Carbon storage

An important ecosystem service

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

Throughout the project we collaborated with stakeholders, as explained in more detail by Schröter et al. (2005b) and De la Vega et al. (in preparation to be submitted to Regional Environmental Change). Stakeholders interested in carbon storage included representatives of national and European forest owners, land owners, agricultural producers, paper industry, consultancy groups to the paper industry, farm management agencies, consultancy groups to environmental engineers, environmental finance companies, national and European representatives of environmental agencies, as well as biomass energy companies and foundations. These stakeholders expressed an
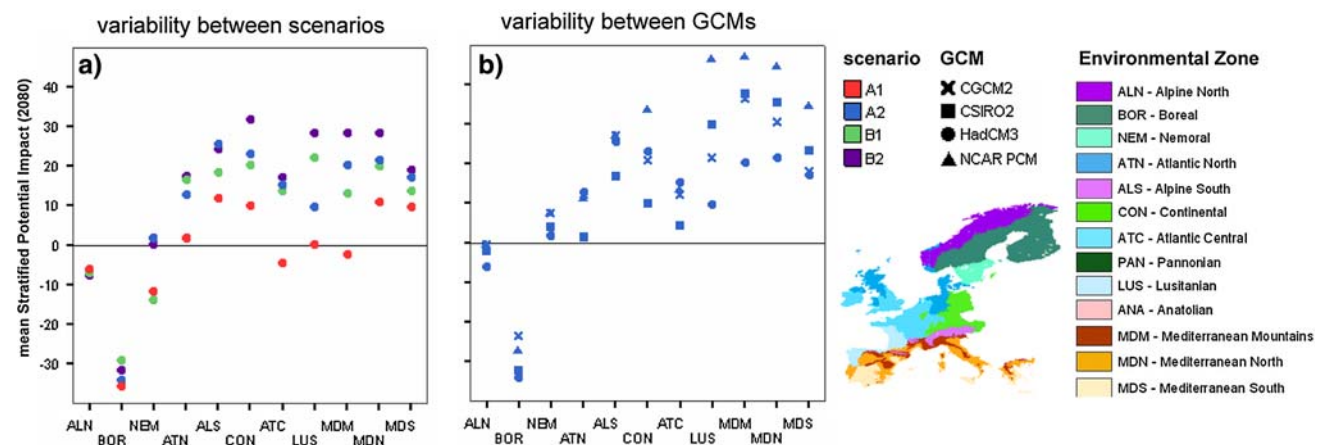

Fig. 9 Scatter plots show the variability in stratified PI for carbon storage in 2080, summarised per Environmental Zone. The plots showing the variability between the GCMs shows that the disagreement between CGMs can be greater than the variability between the scenarios

interest in the carbon storage potential of their land and the carbon budget of the use of biomass energy crops and biomass side products, such as straw from wheat production. Depending on European Union (EU) mitigation policies, these stakeholders may receive credits for carbon storage. Besides estimating carbon storage in Europe's terrestrial ecosystems we therefore also considered the carbon offset of biomass energy crops (including the carbon/energy balance for crop production, transport and energy conversion processes) (see Tuck et al. 2006). However, the example given in this paper refers to regional carbon storage in plants and soils only, not to substitution of fossil fuels with biomass energy crops. Besides the direct commercial interest in carbon storage, stakeholders also mentioned the potential positive side effects of increasing the carbon storage in terrestrial biomass, such as enhanced recreational value of a landscape and possible positive impacts on water purification.

The ecosystem service carbon storage is indicated by the variable NBE, which is provided by the dynamic global vegetation model LPJ (Sitch et al. 2003). The NBE of an area is determined by net primary production (NPP, net carbon uptake by the plants), and carbon losses due to soil heterotrophic respiration, fire, harvesting, and land use change. Net carbon storage is the integral of NBE (sources plus sinks) over time. Net carbon uptake (positive NBE) is valued as an ecosystem service to reduce carbon dioxide concentrations in the atmosphere. Net carbon emission (negative NBE) is regarded as an ecosystem disservice, adding to the atmospheric carbon dioxide concentration. The amounts of carbon that can be efficiently stored in terrestrial vegetation over long periods of time need to be considered in terms of absolute numbers, in relation to other pools and fluxes (atmospheric concentration, anthropogenic emissions, uptake by the oceans) and within the political context.

Results

Figure 9a shows that carbon storage is expected to decrease in the northern EnZs (Alpine North, Boreal, Nemoral), a major adverse effect. The other EnZs in all cases show an increase. 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 values for net carbon emission in Alpine North and Boreal are 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. 9a, there is a very strong difference in the values of PIstr depending on the SRES storylines. The B2 scenario is associated with the largest uptake and smallest emission, while for the A1 scenario the smallest uptake and the largest emission is projected. Figure 9b shows that there is large variability between the GCMs. However, withstanding this variability, there remains a large difference between the northern EnZs and the others.

On the whole, Europe is projected to become a net source of carbon by the end of this century (Zaehle et al. 2004). The greatest source of carbon will be in northern Europe, due to aging forests and temperature effects on soil respiration. While northern Europe is projected to have a high Adaptive Capacity (cf. Fig. 6), 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 act as net carbon sink. In part, this is due to a projected increase in the area under forestry (Kankaanpää and Carter 2004). Furthermore, 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. 2005b). Sustainable intensive management could help retain stored carbon, but will require considerable adaptation in the forestry systems. This will be more difficult in the Mediterranean region, for which a comparatively low Adaptive Capacity is projected (cf. Fig. 6).

Discussion

The current framework was developed with the tools at hand and a wish list of analyses in mind. Strong points in the framework are the multiple scenarios as a measure of variability and uncertainty, the multiple stressors (e.g. socio-economic, land use, and climate change), the stakeholder involvement, and the inclusion of a measure of adaptive capacity. A novel element of the framework is the method of stratifying impacts by regional environments, which makes comparisons possible across the European environment. Furthermore, the stratification procedure allows comparison between PIs of diverse ecosystem services. With the approach described in this paper, it is possible to perform the first comprehensive spatial vulnerability assessment for a region as large as Europe, using outputs from many different ecosystem models (Metzger 2005).

As indicated in Introduction, there is a demand for methods to integrate multidisciplinary assessments and to incorporate measures of adaptive capacity (Kasperson and Kasperson 2001; Schröter et al. 2005a; IPCC 2001a). While such methods are aimed at synthesising findings, there is the risk of oversimplification or blurring initial findings with complex meta-analyses and added uncertainties. The present framework attempted to avoid oversimplification by providing separate vulnerability maps for each ecosystem service output. Furthermore, we feel that for a better comprehension of vulnerability it is important to analyse not only the vulnerability maps, but also the separate components used to derive the vulnerability map. This approach has consequences for the ease of interpretation. A separate software shell (Metzger et al. 2004) had to be developed to make such analyses possible. Any processing of the modelled ecosystem services adds both complexity and uncertainty. In the present approach, this processing comprised three parts. (1) The stratification of the ecosystem service maps adds considerable conceptual complexity, but is of great importance for allowing comparison across the European environment. While both the environmental stratification that is used (Metzger et al. 2005a) and the reference value (ESref) are essentially arbitrary, they can be applied consistently for different ecosystem services and scenarios. (2) The Adaptive Capacity index meets the needs for a macro-scale indicator, although arguably separate indicators should be developed for different sectors or ecosystem services. (3) The visual combination of the two indices results in an intuitive map, but also includes a bias, especially in the scaling of the Adaptive Capacity index (Saturation). The relative contribution of AC can be manipulated by changing the scaling. As the approach is applied, more advanced methods of combining stratified PI (PIstr) and adaptive capacity (AC) may be developed, i.e. through fuzzy logic or qualitative differential equations. However, prerequisite for this is a further understanding how PIstr and AC interact and influence vulnerability.

For easier explanation of our concept for a spatially explicit vulnerability assessment, this paper uses just one ecosystem service. This suffices for illustrating the approach, but it does not allow for the analyses for which the approach was set up, i.e. comparing different ecosystem services. A complete vulnerability assessment will demonstrate the true value of the framework, not the maps of one service in isolation. The maps for net carbon storage foster a risk: for a full comprehension of the true effect of carbon storage, it is paramount to also take areas with net carbon emissions into

account. However, landowners are often interested in carbon storage on its own, especially with the possibility of receiving credit for carbon storage on their land. Vulnerability maps could then help in deciding whether to use available land for carbon storage, or for another ecosystem service, e.g. bio-fuel production or forestry.

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

Perceived well-being, as well as anticipated vulnerability is always based on a normative value judgement. Stakeholders from different sectors may base their value judgement on different assumptions—in other words, some aspects of vulnerability are individual. In our stakeholder dialogue, it became apparent that many stakeholders are more interested in PIs than in generic vulnerability maps. Stakeholders used their individual values to judge the severity of a PI. Furthermore, stakeholders often wished to account for their own individual adaptive capacity when inter-

preting PIs. The generic adaptive capacity index we developed relayed information on the longer-term socio-economic context but their anticipated ability to adapt to change remained largely a matter of personal perception. In a flood-prone area in Germany, it has recently been shown that ''perceived adaptive capacity'' is a major determinant of whether people will take adaptation measures or not (Grotham and Reusswig 2006). It seems that more place-based studies could better take account of the individual nature of vulnerability. One possible consistent method of analysis would be to assess impacts on detailed random sample areas (cf. Bunce and Harvey 1987).

Communication of the results of the vulnerability assessment needs considerable thought, not in the least because of the uncertainties in future changes, and the political sensitivity around European policies that are directly related, such as agricultural reforms and carbon trading. Vulnerability maps, but also maps of the exposure, ecosystem service provision, PIs and adaptive capacity should always be presented as one of a range of possible scenarios. Furthermore, many of the comparisons and analyses can take place in summarised tables or graphs instead of maps, which are more easily misinterpreted. For instance, changes can be summarised per EnZ (Fig. 9) or per country. Similar graphs can be made for the other components of vulnerability, which can also be analysed separately. In the vulnerability-mapping tool (Metzger et al. 2004), all ecosystem services of the ATEAM project can be analysed by creating such graphs. Furthermore, all ecosystem services are presented in fact sheets which not only show all relevant maps, but also give important information about scenarios assumptions, modelling approach and uncertainties.

Vision—a portfolio for the future of Europe

This work was guided by our wish to support stakeholders in decision-making. To enable Europe's people to decide on how to manage their land in a sustainable way, multiple maps of projected ecosystem service provision and adaptive capacity of related sectors could be obtained for all the ecosystem services that are relevant to the people. Like a portfolio that is spatially explicit and shows projections over time (while being honest about the attached uncertainties), different ecosystem services could be seen in their interactions, sometimes competing with each other, sometimes erasing or enforcing each other. This portfolio could provide the basis for discussion between different stakeholders and policy makers, thereby

facilitating sustainable management of Europe's natural resources.

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