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A multidisciplinary multi-scale framework for assessing vulnerabilities to global change

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Abstract

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

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

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

1. Introduction

Many aspects of our planet are changing rapidly due to human activities and these changes are expected to accelerate during the next decades (IPCC, 2001a,b,c). For example, forest area in the tropics is declining, many species are threatened to extinction, and atmospheric carbon dioxide concentration will soon be twice the concentrations in pre-industrial times, resulting in global warming. Many of these changes will have an immediate and strong effect on agriculture, forestry, biodiversity, human health and well-being, and on amenities such as traditional landscapes (UNEP, 2002; Watson et al., 2000). Furthermore, a growing population, with increasing per capita consumption of food and energy, are expected to continue emitting pollutants to the atmosphere, resulting in continued nitrogen deposition and eutrophication of environments (Galloway, 2001; Alcamo, 2002). Both scientists and the general public have become increasingly aware that

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these environmental changes are part of a larger 'global change' (Steffen et al., 2001). Many research projects and several environmental assessments are currently addressing these concerns at different scales,[3] frequently in multidisciplinary collaborations. However, integrating this wealth of information across scales and disciplines remains a challenge (Millenium Ecosystem Assessment, 2003).

This paper aims to quantify these global-change concerns in a regionally explicit way by defining and estimating vulnerabilities. First, we summarise a comprehensive concept initially developed to assess which European *people* or *sectors* may be vulnerable to the loss of particular ecosystem services. These losses can be caused by the combined effects of changes in climate, land use, and atmospheric composition. The approach allows vulnerabilities to be compared across sectors, regions, and alternate futures. Subsequently, we illustrate how this concept can be applied at specific scales as well as across scales. The concepts described in this paper were developed as part of the Advanced Terrestrial Ecosystem Analysis and Modelling (ATEAM) project. Detailed information about the project, as well as a software tool with project results (Metzger et al., 2004), can be found on its website (http://www.pik-potsdam.de/ateam).

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

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

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

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

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

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

The following sections first summarise the concepts of the spatially explicit and quantitative framework that was developed for a vulnerability assessment for Europe, explaining the different tools used to quantify the elements of vulnerability, and how we integrate these elements into maps of vulnerability. Then we

[3] In this paper the term *scale* is used pragmatically to mean the spatial extent and resolution as well as the detail in which processes can be studied.

illustrate how the vulnerability framework can be used to compare information from the global impact model IMAGE (IMAGE Team, 2001) with the European results from ATEAM.

2. The multidisciplinary vulnerability framework

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

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

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

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

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

These simple conceptual functions describe how the different elements of vulnerability are related to each other. Nevertheless, they are not immediately operational for converting model outputs into vulnerability maps. The following sections describe how modelled

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

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

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

maps of any ecosystem service can be converted into vulnerability maps that will allow for multidisciplinary intercomparison, such as between ecosystem services relevant for forestry and agriculture.

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

2.1. Exposure, sensitivity and potential impacts

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

Besides for land use, discussed in the previous section, scenarios were also developed for atmospheric carbon dioxide concentration, climate, socio-economic variables. These scenarios are internally consistent, and

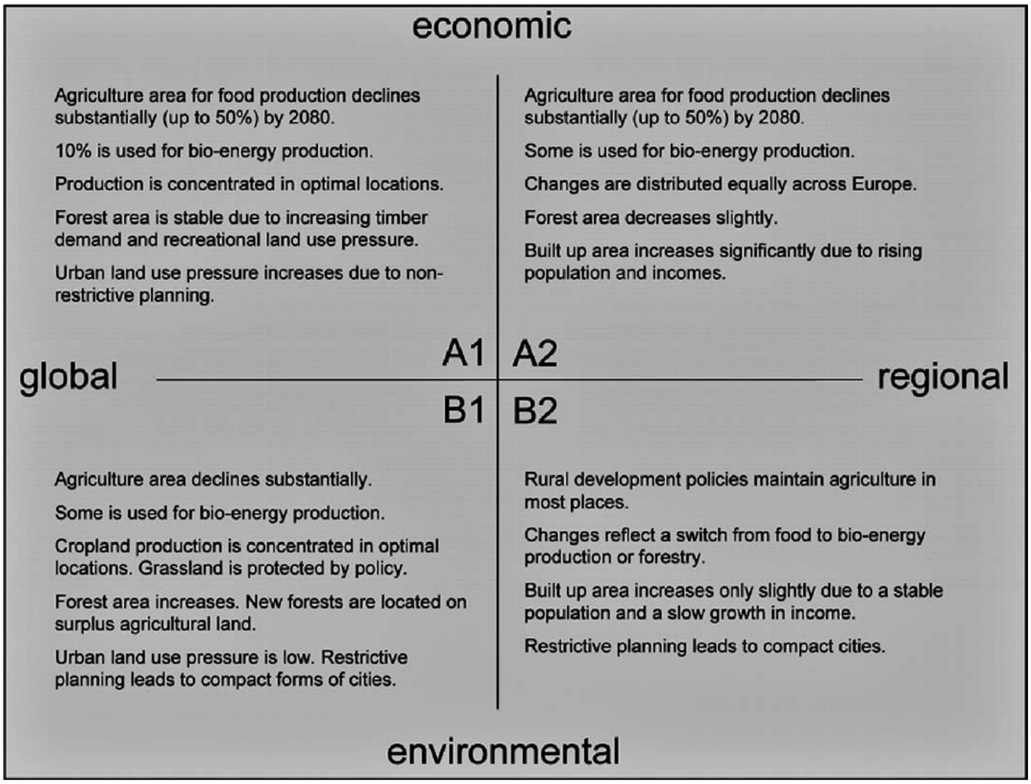

Fig. 1. Summary of the main trends in the ATEAM land use scenarios (Rounsevell et al., 2005), following the IPCC SRES scenarios (Nakicenovic et al., 2000).

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

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

In the examples mapped in this manuscript we restrict ourselves to the ecosystem service 'farmer livelihood' (Fig. 2). For this ecosystem service, the vulnerability approach is illustrated with maps for one GCM, the Hadley Centre Climate Model 3 (HadCM3), and one scenario, the A1 scenario, which assumes continued globalisation with a focus on economic growth. In Section 2.5, the analysis of multiple scenarios is discussed.

2.2. Stratified potential impacts

Our estimation of potential impacts is undertaken at the regional scale, emphasising the differences across the European environment. Simply comparing changes in ecosystem services across Europe provides only a limited analysis of regional differences because ecosystem services are highly correlated with their environments. Some environments have high values for particular ecosystem services, whereas other regions have lower values. For instance, Spain has high biodiversity (5048 vascular plant species (WCMC, 1992)), but low grain yields (2.7 t ha^{-1} for 1998–2000 average (Ekboir, 2002)), whereas The Netherlands has a far lower biodiversity (1477 vascular plant species (van der Meijden et al., 1996)), but a very high grain yield (8.1 t ha^{-1} for 1998–2000 average (Ekboir, 2002)). Therefore, while providing useful information about the stock of resources at a European scale, absolute differences in species numbers or yield levels are not good measures for comparing regional impacts between these countries. Looking at relative change in ecosystem service provision would overcome this problem (e.g. −40% grain yield in Spain versus +8% in The Netherlands), but also has a serious limitation: the same relative change can occur in very different situations. Table 2 illustrates how a relative change of −20% can represent very different impacts, both between and within environments. Therefore, comparisons of rela-

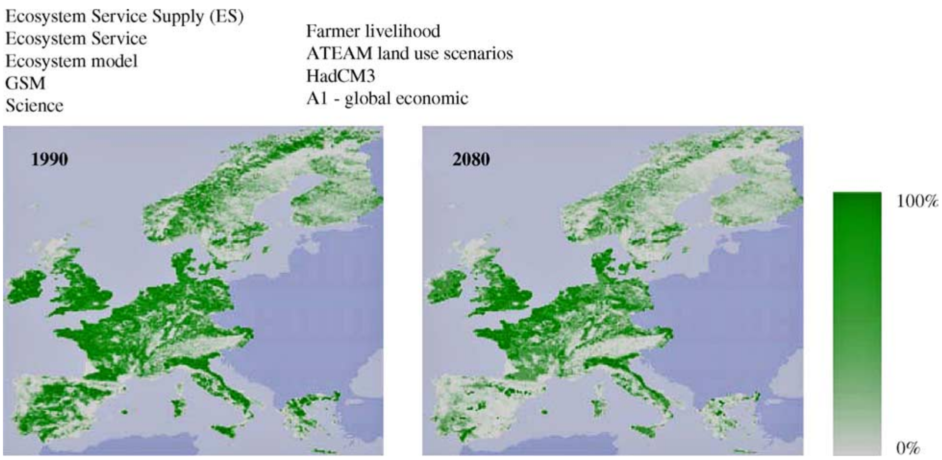

Fig. 2. Ecosystem service supply indicator for 'farmer livelihood', as modelled by the ATEAM land use scenarios for baseline conditions and the A1 scenario for the 2080 time slice.

Table 2
Example of changing ecosystem service supply (e.g. grain yield in t ha^{-1} y^{-1}) in four grid cells and two different environments between two time slices (t and $t + 1$)

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

tive changes in single grid cells must be interpreted with great care and cannot easily be compared.

For a meaningful comparison of grid cells across Europe it is necessary to place potential impacts in their regional environmental context, i.e. in a justified cluster of environmental conditions that is suited as a reference for the values in an individual grid cell. Because environments will alter under global change, consistent environmental strata must be determined for each time slice. We used the recently developed Environmental Stratification of Europe (EnS) to stratify the modelled potential impacts (Metzger et al., 2003; Metzger et al., 2005). The EnS was created by statistical clustering of selected climate and topographical variables into 84 strata. For each stratum a discriminant function was calculated for the variables available from the climate change scenarios. With these functions the 84 climate classes were mapped for the different GCMs, scenarios and time slices, resulting in 48 maps of shifted climate classes. Maps of the EnS, for baseline and the HadCM3-A1 scenario are mapped in Fig. 3 for 13 aggregated environmental zones. With these maps, all modelled potential impacts on ecosystems can be placed in their environmental context consistently.

Within an environmental stratum ecosystem service values can be expressed relative to a reference value. While any reference value is inevitably arbitrary, in order to make comparisons it is important that the stratification is 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 environ-

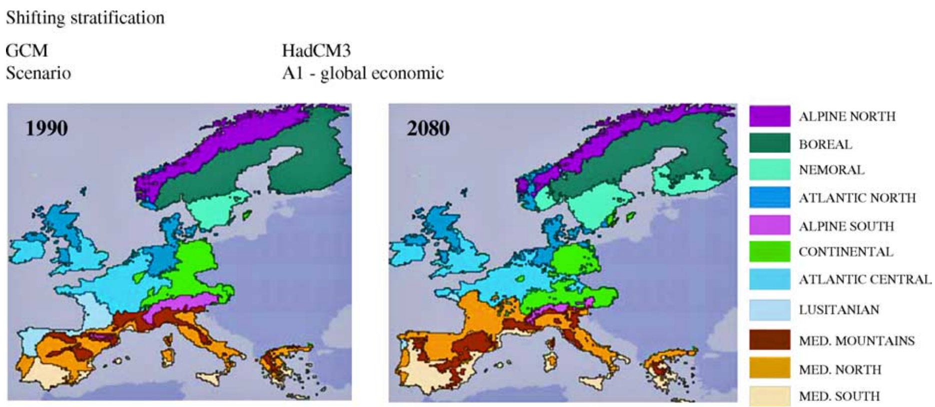

Fig. 3. Environmental Stratification of Europe (EnS), in 84 strata, here aggregated to environmental zones for presentation purposes.

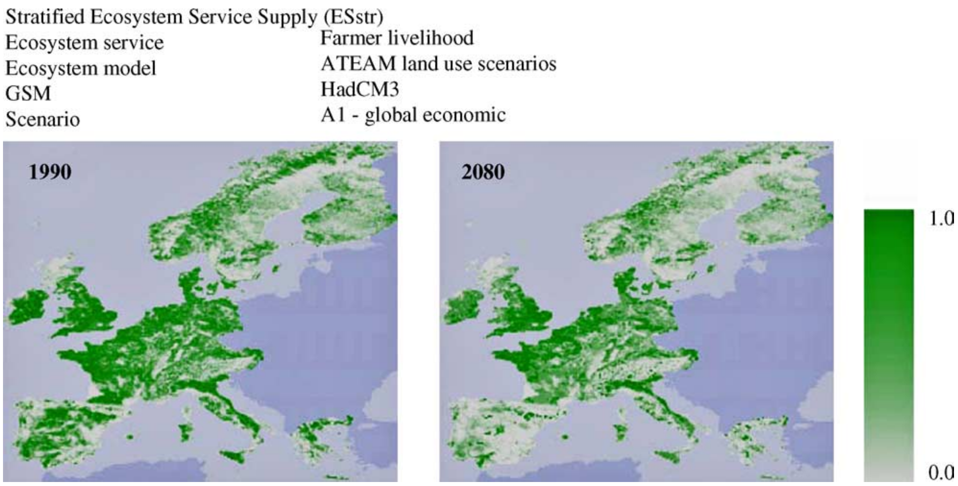

Fig. 4. Stratified ecosystem service supply for the ecosystem service indicator 'farmer livelihood'. The ecosystem service supply maps for 'farmer livelihood' (Fig. 1) are stratified by the environmental strata (Fig. 3).

mental 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 of the ecosystem service provision (ESstr) with a 0–1 range for the ecosystem service in the grid cell:

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

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

In this way a map is created in which potential impacts on ecosystem services are stratified by their environment and expressed relative to a reference value (Fig. 4). Because the environment changes over time, both the reference value and the environmental stratification are determined for each time slice. As shown in Fig. 4, the stratified ecosystem service provision map shows more regional detail than the original non-stratified map. This is the regional detail required to compare potential impacts across regions (see also Table 2). The change in stratified ecosystem service provision compared to baseline conditions shows how potential changes in ecosystem services affect a given location (see also Table 2). Regions where ecosystem service supply relative to the environment increases have a positive change in potential impact and vice versa (see Fig. 5). This is for instance the case when environmental conditions become less favourable for growing wheat, but yield levels are maintained. 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 the stratified potential impact, ESstr the stratified ecosystem service supply, es the ecosystem service, x a grid cell, s a scenario, t a time slice, and baseline = 1990.

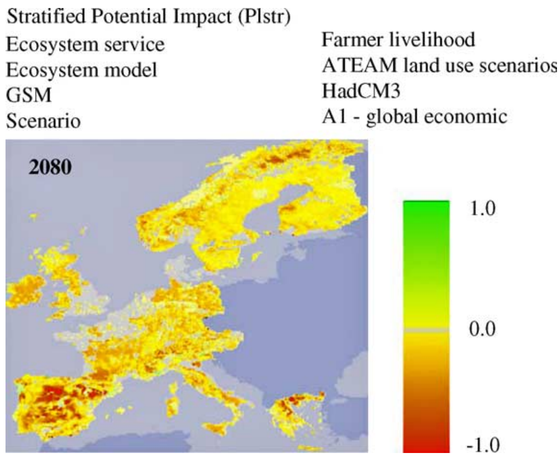

Fig. 5. Stratified potential impact for the ecosystem service indicator *Farmer livelihood*. Positive values indicate an increase of ecosystem service provision relative to environmental conditions, and therefore a positive potential impact, while negative potential impacts are the result of a relative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

2.3. Adaptive capacity index

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

The concept of adaptive capacity was introduced in the IPCC Third Assessment Report (IPCC, 2001a). According to the IPCC, factors that determine adaptive capacity to climate change include economic wealth, technology and infrastructure, information, knowledge and skills, institutions, equity and social capital. So far, only one study has made an attempt at quantifying adaptive capacity based on observations of past hazard events (Yohe 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. In ATEAM we developed a generic index of macro-scale adaptive capacity. This index is based on a conceptual framework of socio-economic indicators, determinants and components of adaptive capacity, e.g. GDP per capita, female activity rate, income inequality, number of patents, and age dependency ratio (Schröter et al., 2003; Klein et al., 2005). The index is calculated for smaller regions (i.e. provinces and counties) and differs for each SRES scenario. The index does not include individual abilities to adapt. An illustrative example of our spatially explicit generic adaptive capacity index over time is shown in Fig. 6, for the A1 scenario. Different regions in Europe show different adaptive capacities—under this A1 scenario, lowest adaptive capacity is expected in the Mediterranean, but the differences decline over time.

2.4. Vulnerability maps

The different elements of the vulnerability function (Eq. (3)) have now been quantified (cf. Fig. 7). The last step, the combination of stratified potential impact (PIstr) and the adaptive capacity index (AC), is however the most dangerous step, especially when taking into account the limited empirical basis of the adaptive capacity index. It was therefore decided to create a visual combination of PIstr and AC without quantifying a specific relationship. The vulnerability maps (Fig. 8) illustrate which areas are vulnerable. For further analytical purposes the constituents of vulnerability, the changes in potential impact and the adaptive capacity index, will have to be viewed separately.

Trends in vulnerability follow the trend in potential impact: when ecosystem service supply decreases, humans relying on that particular ecosystem service become more vulnerable in that region. Alternatively, vulnerability decreases when ecosystem service supply increases. Adaptive capacity lowers vulnerability. In regions with similar changes in potential impact, the region with a high AC will be less vulnerable than the region with a low AC. The Hue saturation value (HSV) colour scheme is used to combine PIstr (Fig. 5) and AC (Fig. 6). The PIstr determines the Hue, ranging from red (decreasing ecosystem service provision, $\text{PIstr} = -1$, highest negative potential impact) via yellow (no change in ecosystem service provision, $\text{PIstr} = 0$, no potential impact) to green (increase in ecosystem service supply,

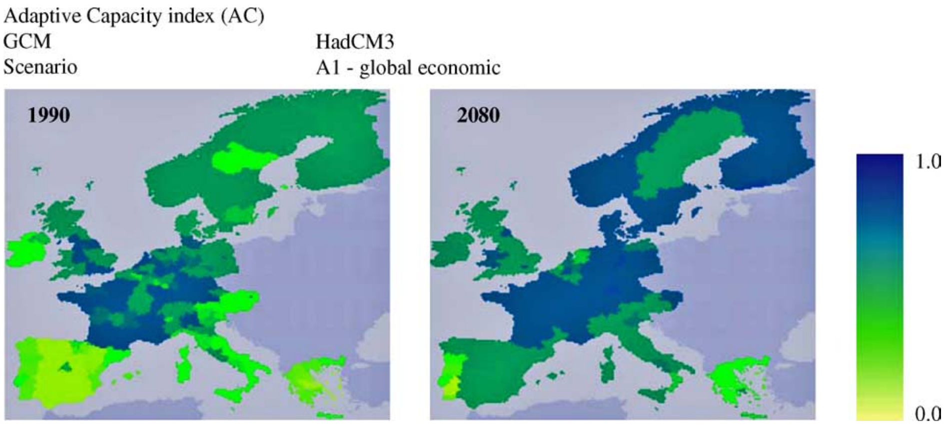

Fig. 6. Socio-economic indicators have been aggregated to a generic adaptive capacity index. Trends in the original indicators were linked to the SRES scenarios in order to map adaptive capacity in the 21st century.

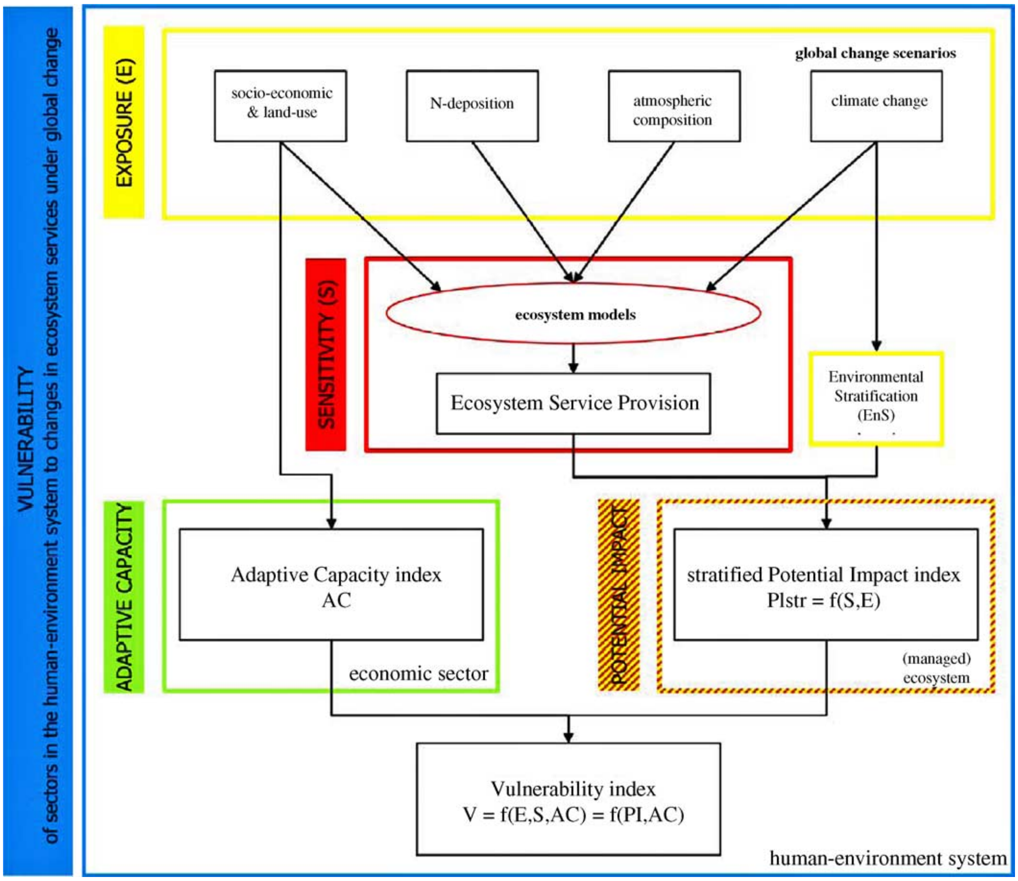

Fig. 7. Summary of the ATEAM approach to quantify vulnerability. Global change scenarios of exposure are the drivers of a suite of ecosystem models that make projections for future ecosystem services supply for a 10 arcmin × 10 arcmin spatial grid of Europe. The social-economic scenarios are used to project developments in macro-scale adaptive capacity. The climate change scenarios are used to create a scheme for stratifying of potential impacts supply to a regional environmental context. Changes in the stratified ecosystem service supply compared to baseline conditions reflect the changing potential impact of a given location. The changes in potential impact and adaptive capacity indices can be combined, at least visually, to create European maps of regional vulnerability.

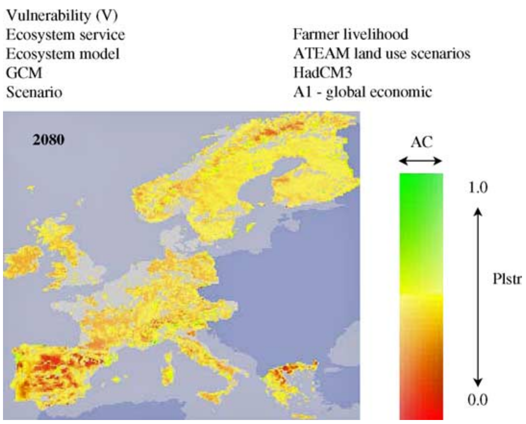

Fig. 8. Vulnerability maps for the ecosystem service indicator 'farmer livelihood'. These maps combine information about stratified potential impact (Fig. 5) and adaptive capacity (Fig. 6) as illustrated by the legend. An increase of potential impact decreases vulnerability and visa versa. At the same time vulnerability is lowered by human adaptive capacity.

PIstr = 1, highest positive potential impact). Note that it is possible that while the modelled ecosystem service supply (Fig. 2) stays unchanged, stratified potential impact increases or decreased due to changes in the highest value of ecosystem service supply in the environmental stratum (ESref). Thus, when the environment changes this is reflected in a change in potential impact.

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

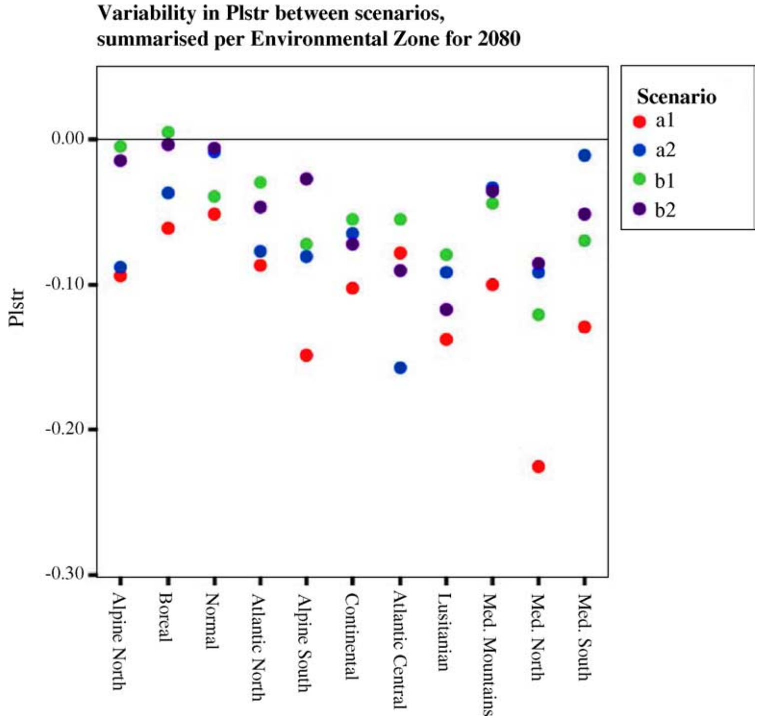

Fig. 9. Summary of mean stratified potential impacts (PIstr) for different environmental zones. These summary plots help in analysing the impacts of multiple scenarios in different regions.

The last element of the HSV colour code, the Value, was kept constant for all combinations. Fig. 8 shows the vulnerability maps and the legend for farmer livelihood under the A1 scenario (see also Fig. 1) for the HadCM3 GCM. Under this scenario farmer livelihood will decrease in the extensive agricultural areas. The role of AC becomes apparent in rural France and Spain, where France is less vulnerable than Spain due to a higher AC, i.e. a supposed higher ability of the French agricultural sector to react to these changes.

2.5. Analysis of the maps

Spatially modelling ecosystem services and potential impacts and vulnerability clearly shows that global changes will impact ecosystems and humans differently across Europe. Therefore, these maps provide insights that cannot be obtained through non-spatial modelling. However, interpreting the spatial patterns portrayed in the multitude of maps (related to multiple ecosystem services, scenarios, and time slices) is difficult. To make the results more accessible, both to stakeholders and scientists, many of the analyses can take place in summarised form. For instance, changes can be summarised per (current) environmental zone (EnZ) (Fig. 3, 1990) or per country. In such graphs, multiple scenarios can be analysed for different regions. Similar graphs can be made to examine the development over time for a specific region. All maps generated by the ATEAM projects are available in a software tool that allows both simple map queries and the construction of summarising scatter plots (Metzger et al., 2004).

Fig. 9 gives an example of a summary of the changes in PIstr for the 2080 time slice (compared to baseline). Similar graphs can be made for the other components of vulnerability and to illustrate variability between modelled results obtained using climate change scenarios generated by different GCMs, as demonstrated in Metzger et al. (2004). The results presented in Fig. 9 show that the scenarios, described in Section 2.1 and Fig. 1, affect PIstr differently in the different regions. In most cases the A1 scenario has the most negative impact. However, in the Atlantic Central the A2 and B2 scenarios project greater changes. The B1 scenario most frequently shows the smallest impact, but not in the Mediterranean South, where it comes third, after A2 and B2.

3. Multi-scale comparisons of vulnerability

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

3.1. Vulnerability maps at different scales

It is generally recognised that ecosystem components determine spatial environmental patterns through a scale-dependant hierarchy. On a global or continental scale, climate and geology determine the main patterns. They are conditional for the formations of soils, which in turn determine the local potential vegetation. There are feedbacks in the other direction, for example vegetation also influences soil properties and can even influence local climate. Most ecosystem patterns are, however, caused by the above-mentioned hierarchy (Bailey, 1985; Klijn and de Haes, 1994). On a European scale, climate and geomorphology are recognised as the key determinants of ecological patterns; these are followed by geology and soil. The variables that were clustered to create the European Environmental Stratification, which was used to stratify ecosystem service supply in Europe as described above, were selected with this conceptual hierarchical model in mind (Metzger et al., 2003, 2005).

In studies where ecosystem service supply is modelled at other scales, e.g. globally or at the catchment level, similar quantitative stratifications can be created using variables that are appropriate for that particular scale. With these stratifications it will then be possible to stratify potential impacts. At the global scale, several modelled maps of potential natural vegetation or biomes are available that could form suitable quantitative stratifications and are also linked to global change scenarios. Fig. 10 shows how global stratified potential impact maps can be created in the same way as depicted in Fig. 5 for Europe, using data from the dynamic integrated assessment modelling framework IMAGE 2.2 (IMAGE Team, 2001). IMAGE was developed over the last 15 years and has been used extensively to explore potential impacts of global change at the global level. Potential natural vegetation (biomes), as modelled by IMAGE, is used to stratify the ecosystem service food crop production. Because no adaptive capacity index is available at the global scale it is not possible at this time to create vulnerability maps, as shown in Fig. 8.

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

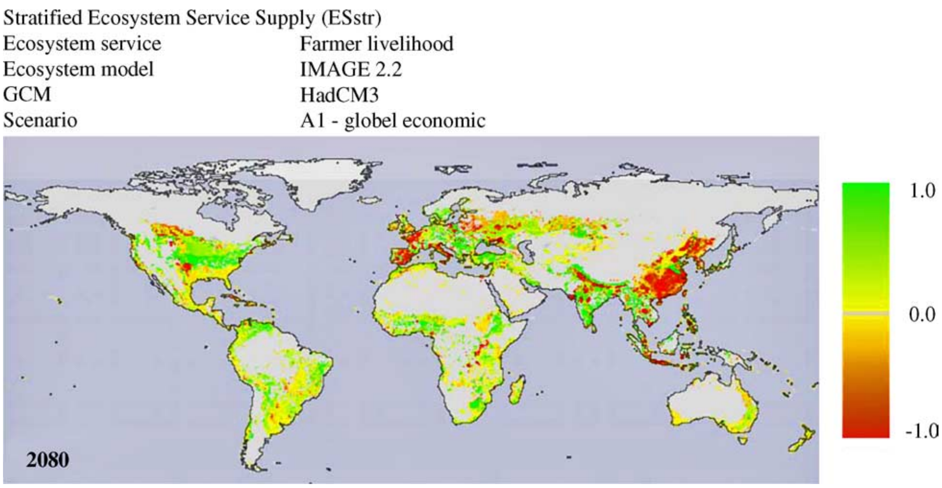

Fig. 10. Stratified potential impact for the ecosystem service indicator 'total crop production' for the SRES A1 scenario. Positive values indicate an increase of ecosystem service provision relative to environmental conditions, and therefore a positive potential impact, while negative potential impacts are the result of a relative decrease in ecosystem service provision compared to 1990.

3.2. Comparing across scales

As demonstrated above, vulnerability maps at different scales can be created, as long as both a suitable quantitative stratification and adaptive capacity data are available. However, while stratified potential impact and vulnerability maps of different scenarios or sectors can be compared at one scale, the European maps of Fig. 5 cannot be compared to the global maps of Fig. 10 because these maps are based on different stratifications. This can be overcome by either applying the IMAGE biome stratification on the ATEAM data or vice versa.

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

The strength of agreement between an aggregation of the EnS and the IMAGE biomes was determined by calculating the Kappa statistic (Monserud and Leemans, 1992). For the Kappa analysis the datasets that are compared must have the same spatial resolution, and distinguish the same classes. To meet these requirements the EnS was resampled to the IMAGE resolution. Nearest nearest-neighbour assignment was used, as this will not change values of categorical data. The maximum spatial error is half a 0.5° gird cell. In addition, the two classifications were clipped to the largest overlapping extent. A contingency matrix was calculated to determine the best way to aggregate the EnS strata. Kappa, 0.719, could then be calculated using the Map Comparison Kit (Visser, 2004), which indicates a 'very good' strength of agreement between the aggregated EnS and the IMAGE biomes (Monserud and Leemans, 1992). Fig. 11 shows the Kappa statistic for the whole map as well as for the different biomes.

The strong agreement between the aggregated EnS and the IMAGE biomes indicates that it is possible to stratify the fine resolution ATEAM model outputs by

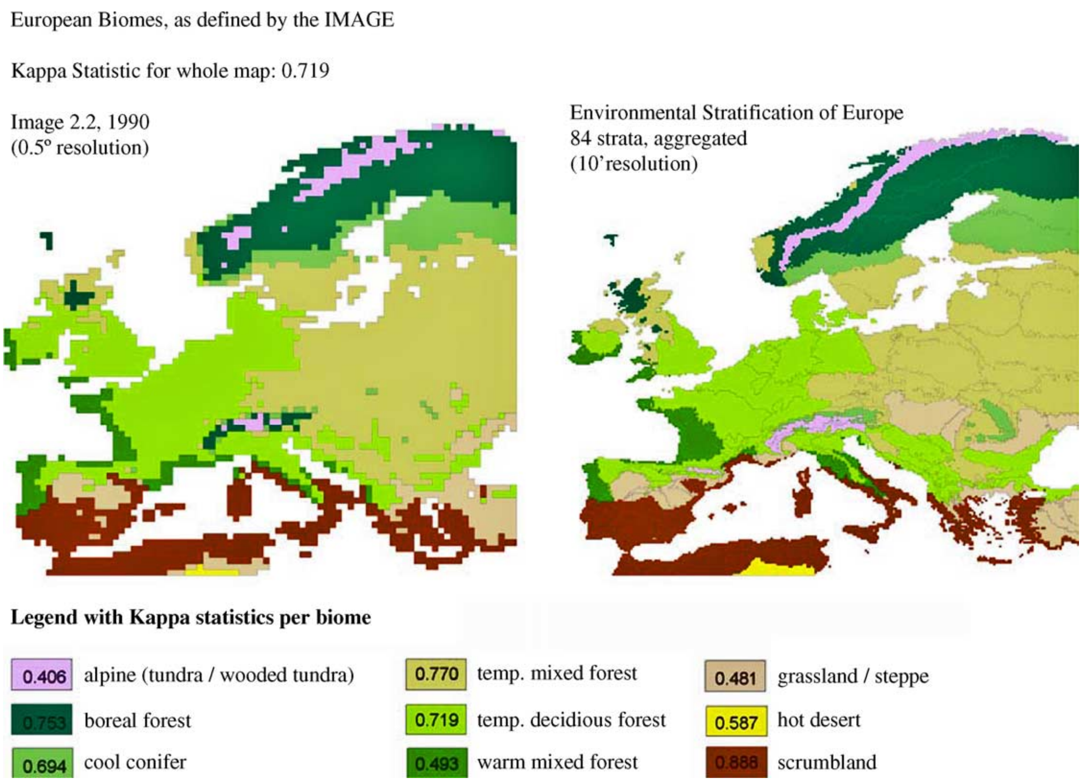

Fig. 11. The 84 strata of the Environmental Stratification of Europe (EnS) can be aggregated to resemble the IMAGE biomes. The Kappa statistic, 0.719 for the whole map, indicates a 'very good' agreement between both maps (Section 3.2).

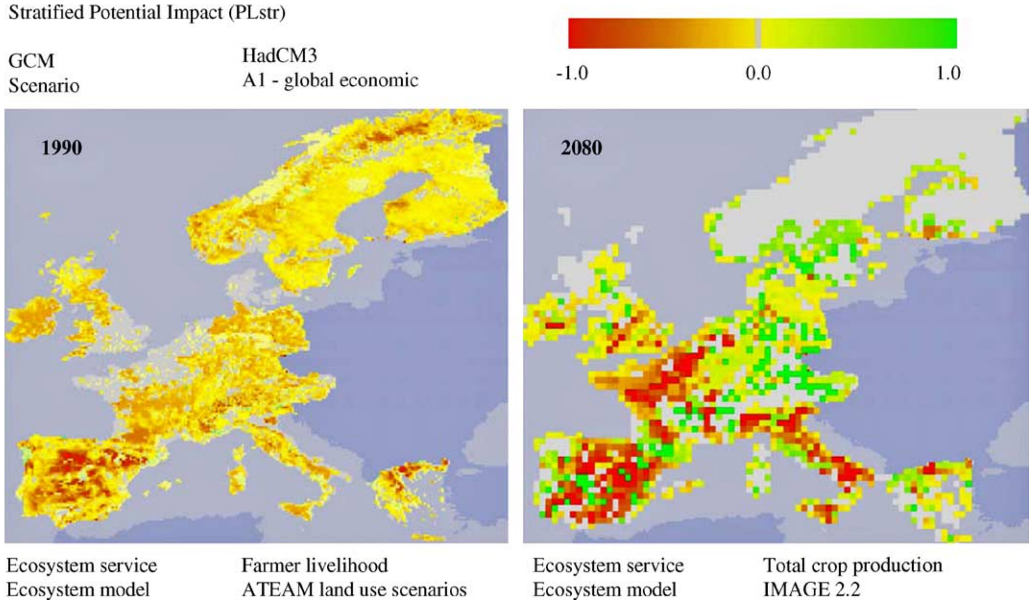

Fig. 12. Maps of changing potential impacts for the ecosystem services 'farmer livelihood' (10 arcmin resolution) and 'total crop production' (0.5° resolution). Because both maps were created using the same stratification, they can be compared.

the IMAGE biomes, thus placing the European maps in the global context. The resulting European maps of stratified potential impact of farmer livelihood at 10 arcmin × 10 arcmin resolution can now be compared to the global maps of 'total crop production' derived from IMAGE, as shown in Fig. 12.

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

4. Discussion and conclusions

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

The current framework was developed with the tools at hand and a wish list of analyses in mind. Strong points in the framework are the multiple scenarios as a measure of variability and uncertainty, the multiple stressors (CO_2 concentrations, climate, and land use), the inclusion of a measure of adaptive capacity, and the possibility to make comparisons across different scales. The approach, as presented here, will facilitate the analysis of the ecosystem services estimated by ecosystem models. As the approach is applied, more advanced methods of combining stratified potential impact (PIstr) and adaptive capacity (AC) may be developed. However, prerequisite for this is a further understanding of how PIstr and AC interact and influence vulnerability, which may only be feasible when empirically analysing specific cases. Ideally, the AC index will eventually be replaced by sector specific projections of adaptive capacity. Some qualitative information, or knowledge shared during stakeholder dialogues does not enter the approach in a formal way. Therefore, it is imperative to discuss the results with stakeholders, experts and scientists as part of the analysis.

Communication of the results of a vulnerability assessment will need considerable thought, not in the least because of the uncertainties in future changes, and the political sensitivity around (European) policies that are directly related, such as agricultural reforms and carbon trading. Vulnerability maps, as well as maps of the exposure, ecosystem service supply, PI, PIstr, and AC, should always be presented as one of a range of possible scenarios. Furthermore, many of the comparisons and analyses can take place in summarised tables or graphs, that can present multiple scenarios and time slices, instead of single maps, as shown in Fig. 9.

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

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

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