Vulnerability to Changes in Ecosystem Services

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It is available at http://www.cid.harvard.edu/cidwp/grad/010.htm. However, as a work in progress, this does not constitute formal publication, and comments are especially welcome and may be directed to the author via email at dagmar.schroeter@gmail.com or via telephone at +1 617-447-8479.

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The Science, Environment and Development Group at Harvard's Center for International Development collaborates internationally on a variety of research projects and outreach activities that seek to improve society's understanding of interactions between human development and the natural environment, and to harness that understanding in support of a transition towards sustainability. The Group builds bridges between the local, place-based character of many sustainability challenges and the increasingly global context within which solutions to those challenges must be shaped. It is concerned with the role of "partnerships" among governments, civil society, the private sector, and academia in shaping solutions.

Further information on the Science, Environment and Development Group at Harvard's Center for International Development can be found at http://www.ksg.harvard.edu/sed or by contacting Nancy Dickson at nancy_dickson@harvard.edu.

Abstract

Humans are an inseparable part of their environment through their dependence on ecosystems and the services ecosystems provide. The mismanagement of ecosystem services increases human vulnerability. Examples like the Irish Potato Famine (1845-1850), the Canadian dustbowl (1920s), or the current Californian pollination crisis show how past unsustainable use of ecosystem services lead to human harm. Projections of ecosystem service supply under global change alert us to potential negative trends in the future. Using these examples the author discusses three general reasons for unsustainable management of ecosystem services, and explores how environmental science can facilitate sustainable management. Environmental scientists alone cannot provide the information and the tools that are needed to lessen the vulnerability of a region. However, they can make essential contributions by identifying ecosystem services, and providing the best current understanding of the dynamics of complex ecosystems, including human management. Sustainable management of ecosystem services requires a sustained active dialogue between a free media, an alert and well-informed public, candid scientists and policy makers – in other words, it requires abundant social, economic and environmental resources.

Keywords: vulnerability, sustainability, ecosystem services, historical case study, scenarios, stakeholder dialogue, environmental science, sustainable management

JEL Codes: Q01, Q20, Q30, Q42, Q57

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Introduction — The environmental dimension of vulnerability

Vulnerability is immediately and intuitively understood as the risk of harm and, consequently, suffering. The complexity of this widely used concept arises when we think about who is vulnerable to what, and why? Humans cause or influence their own vulnerability in a complex manner. We have short and long-term, linear and non-linear, direct and indirect influences on a multitude of contributing factors, and vice versa. We are an inseparable part of our environment through our dependence on ecosystems and the services they provide. Our understanding of our own and other people's vulnerability influences whether or not we take action to prevent threatening events from happening (mitigation) or to alleviate their effects (adaptation). We may misconceive sustainable management as a luxury for environmentalists, if we fail to recognise our dependence on ecosystems. In this chapter I will argue that the mismanagement of ecosystem services increases *human* vulnerability. I will give examples of how unsustainable management of ecosystem services led to vulnerability in the past. I then present some future projections of ecosystem service supply and vulnerability in Europe. Finally, I discuss three general reasons for unsustainable management of ecosystem services, and explore how environmental science can facilitate sustainable management.

Ecosystems, ecosystem services and human well-being

In the recent decades we have moved from understanding humans as being reactive to their environment (pre 1980s), to thinking of *environmental crises* as being caused by humans (1980s), to thinking of *environmental crises* as being caused by *socio-natural interaction* (1990s, van der Leeuw 2001). In the present decade, we begin to understand *human crises* as caused by socio-natural interaction. Surely not every human crisis is rooted in an environmental crisis. But every environmental crisis is a human crisis – we refer to a change in our environment as a crisis, when it threatens our livelihood or well-being. Humans rely on ecosystems, because they depend on ecosystem services (de Groot 1992, Daily 1997). Ecosystems offer provisioning services (e.g. food, fresh water, fuelwood, biochemicals), regulating services (e.g. climate and disease regulation, pollination), cultural services (e.g. spiritual, recreational, and aesthetic value, inspiration) and supporting services (e.g. soil formation, nutrient cycling, primary production). They influence our security, basic material for a good life, health, good social relations and ultimately our freedoms and choices, in short our well-being (Millennium Ecosystem Assessment 2003). We are bound to the human perspective, even if we recognise the intrinsic value in ecosystems and biodiversity.

Ecosystem services weave people into ecosystems (environments of interacting animals, plants and microbes (Daily and Ellison 2002)). Social systems and natural systems are inseparable. The recognition of this fact is evident in new terms, such as 'human-environment system' (Turner et al. 2003, Schröter et al. 2005 (in press)). 'socioecological system' (Palmer et al. 2004), 'nature-society system' (Kates et al. 2001), 'eco-social system' (Waltner-Toews et al. 2003), 'linked social-ecological system' (Holling 2001, Walker et al. 2002), and 'combined human-nature system' (Gunderson et al. 1995). In this chapter I understand ecosystems as follows: Ecosystems are environments of interacting animals (including humans), plants and microbes. In doing so I risk over-simplifying human interactions within ecosystems, because currently our models of ecosystems represent complex social interactions as poorly, as economic and social models represent complex ecological interactions. The ultimate goal is to construct models that represent ecosystems adequately, including all relevant social, economic and environmental elements and interactions.

Global change, ecosystem services and vulnerability

During the present century society will increasingly be confronted with global changes such as population growth, pollution, climate and land use change. By 2050, the human population will probably be larger by 2 to 4 billion people (Cohen 2003). The atmospheric carbon dioxide concentration will at least double compared to pre-industrial times, while the global average surface temperature is projected to increase by 1.4-5.8°C (Houghton et al. 2001). Land use changes will have an immediate and strong effect on agriculture, forestry, rural communities, biodiversity and amenities such as traditional landscapes, especially in a continent as densely populated as Europe (Watson et al. 2000). Plausible scenarios of severe changes like these, as well as evidence of past anthropogenic impacts on the environment (cf. Smith et al. 1999, Sala et al. 2000, Stenseth et al. 2002, Walther et al. 2002, Parmesan and Yohe 2003, Root et al. 2003) have led to a growing awareness of potential impacts of global change. Traditionally, this effect on the environment has been seen as additional effect of global change, besides its effects on for example food and fibre production, health, recreation and settlement (Figure 1 A). In contrast to this view, the ecosystem service concept leads to the recognition that ecosystems mediate global change (Figure 1 B). Therefore, environmental impacts of global change can add to human vulnerability by altering the supply of ecosystem services (Schröter et al. 2004b, Metzger and Schröter 2005 (in review)).

Cases of vulnerability

Examples from the past and present

Global change vulnerability is the likelihood that a specific coupled human-environment system will experience harm from exposure to stresses associated with alterations of societies and the environment, accounting for the process of adaptation (Schröter et al. 2005 (in press)). Vulnerability assessments aims to inform decision-making *today* by estimating the likelihood of adverse *future* outcomes given a range of socio-economic and environmental assumptions. Because of these assumptions about the future, the validity of vulnerability assessments can only be empirically tested in hindsight. Since vulnerability is a fairly young concept, to date, no vulnerability assessment has become of age so that it could be validated. An analysis of past damage events based on the vulnerability concept can demonstrate its usefulness, as shown by the insightful vulnerability study of the Irish Potato Famine 1845-1850 (Fraser 2003). Another goal of this exercise is to identify adaptive actions that could have lessened vulnerability before the damage occurred in order to shed light on adaptation processes today. Which types of information would have been useful to which agents and could have altered the outcome of the historical event?

The Canadian dust bowl – Fertility gone with the wind

The following example is taken from *An Environmental History of the Twentieth-Century World*, (McNeill 2001), which analyses historical cases of environmental exploitation. The case illustrates how agricultural livelihood depends on providing and supporting ecosystem services.

The Palliser Triangle of western Canada was considered unsuitable for human settlement by early inquiry of the Royal Geographical Society in 1857. Nevertheless the arrival of the Canadian Pacific Railway initiated settlement of the area at the end of the century. After 1897, the prairies enjoyed a run of rainy and therefore fertile years, and its farming population grew tremendously in consequence. Additionally, high wheat prices around the world during World War I enhanced the trend of increased farming in this semiarid wheat belt. The settlers came mainly from humid lands in eastern North America and Europe. They sought to preserve soil moisture in the summer by leaving fields fallow – an idea widely promoted by professors and agronomists, but nevertheless unsuitable for the windy prairie. By the 1920s, this practice combined with dry years led to serious wind erosion. As droughts brought dust storms, thousands of farm families gave up. An agricultural area the size of Belgium was completely destroyed for farming. Social and economic distress was similar to the Dust Bowl of the American plains (c. 1931-1938).

What could have lessened the vulnerability of the farming population prior to this exodus? An impression of the long-term climate in this region may have lessened the hopeful flow of settlers during a few good seasons in the first place. Furthermore, knowledge that the transfer of farming methods from humid lands would favour soil erosion in the semiarid, windy prairie would have been helpful. Farming families may have adapted their management practice and sustained fertility of their land enough to make a living. As it was, the ecosystem service *soil fertility maintenance* was compromised for the exploitation of the ecosystem service *food and fibre production*. The latter is the obvious target when farming, while the former, supporting service is just as vital. Vulnerability could have been lessened by an awareness and understanding of the vital interplay between these ecosystem services.

Pollination – What the bees do when no one is looking

Pollination, the transfer of pollen from one flower to another,[1] is critical to fruit and seed production. Insects and other animals pollinate flowers on their hunt for nectar, pollen or other floral products. In fact, wild and farmed animals provide pollination services to over three-quarters of the staple crop plants that feed humans (Nabhan and Buchmann 1997). According to the US Department of Agriculture, the European honeybee alone adds $ 14 billion a year to US crops (Holden 2004). However, both wild and cultivated populations of pollinators are declining (Buchmann and Nabhan 1996). The commercially cultivated honeybee population of the US decreased by more than half, from 5.9 million colonies in 1947 to 2.6 million colonies in 2000 (Daily and Ellison 2002). The decline of pollinators is attributed to habitat loss, pesticide poisoning, diseases and pests (Ingram et al. 1996).

California produces 80% of the world's almond supply, with a $ 1.19 billion almond industry (Oberthur 2004). The industry relies on honeybee cultures. Almond farmers rent hives from beekeepers to be put on the blooming orchards. More than 1 million honeybee hives are needed to pollinate the almond groves in California's Central Valley alone. Serious bee shortages in the bee keeping business are brought about by a number of diseases, such as bacterial foulbrood, fungal chalkbrood, nosema (caused by a protozoan) and parasitic mites.

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[1] More precisely, pollination is the process of moving pollen from the anthers (pollen-containing part of the floral stamens) of one flower to the stigma (receptive end of the carpel) of another.

Another problem is the Africanized bee,[2] which breeds with managed honeybees and makes their offspring too aggressive to handle. For the first time in 1994, local bee shortages forced many California almond growers to import the bulk of the honeybees they needed from other states. The price to rent a hive for ca. 5 weeks climbed from 43$ in 2003, over 48-53$ in 2004 to 75-85$ in 2005 (*California Farm Bureau Association*).

Pollination is no longer a matter of course. Habitat loss and pesticides diminish the wild pollinators, while pests and diseases torment the cultivated honeybees. We have compromised the ecosystem service *pollination* for the short-term maximisation of *food and fibre production*. Hedgerows and wild habitat were eradicated to farm more land to increase the harvest, and thereby diminished the habitat that sustained pollinator abundance and diversity. Pesticides are used to the extent that their intended effect of increasing the harvest is counteracted by the lack of pollinators to produce a fruit in the first place. In contrast, some organic farmers use no pesticides, but maintain hedgerows and wild habitat so successfully that they do not have to rent cultivated pollinators (Daily and Ellison 2002). An awareness of the sensitivity of pollinator populations, wild and cultivated, could have prevented the rapid decline now known as "pollinator crises" to the US Department of Agriculture. However, knowledge to support farmers in their efforts to overcome the pollination crisis is sparse. How much land do they need to put aside to maintain a sufficient wild pollinator community? This is one of the many questions that is currently investigated by applied ecologists (e.g. Kremen et al. 2004). The growing awareness of pollination as an essential ecosystem service facilitates research that can increase the adaptive capacity of farmers in this respect.

Ecosystem services and vulnerability in Europe – Projections into the future

The concern for global change and its effects on the supply of a range of ecosystem services during the present century motivated a recently completed European vulnerability assessment[3] (Schröter et al. 2004a, Schröter et al. 2004b). This spatially explicit vulnerability assessment was based on multiple plausible global change scenarios,[4] a framework of ecosystem models, and a continuous stakeholder dialogue. The aim of this study was to help European stakeholders prepare for global change. The central question was: How much will the provision of ecosystem services in Europe change due to the combined effects of climate and land use changes? In the following I will highlight selected findings regarding this question.

Scenarios of climate and land use change

Plausible descriptions of socio-economic and biophysical variables into the present century cover a range of possible futures, without assigning probabilities to any individual scenario. To deal with this uncertainty, the assessment was based on a set of multiple, internally consistent scenarios for the main global change drivers (socio-economic factors, atmospheric greenhouse gas concentrations, climate factors, and land use). These scenarios cover Europe

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[2] Africanized bees arrived in Texas in 1990, after migrating steadily North since 1956, when African bees escaped from a geneticist's laboratory in Brazil. They interbred with local European honeybees and produced so-called Africanized bees.

[3] ATEAM – Advanced Terrestrial Ecosystem Analyses and Modelling, www.pik-potsdam.de/ateam

[4] Scenarios, or alternative imaginations of the future can be used to assess the medium and long-term consequences of global change. A scenarios is a plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technology change, prices) and relationships (Watson and the Core Writing Team 2001).

on a regional spatial scale through this century (EU15 plus Norway and Switzerland, henceforth referred to as EU15+, on a 10'x10' latitude/longitude grid resolution; time slices 2020, 2050, 2080 and baseline 1990). [5] The scenarios were developed from an interpretation for the European region of the global IPCC SRES storylines A1f, A2, B1 and B2 (Nakicenovic and Swart 2000).[6] By using these storylines as a common starting point, socio-economic change relates directly to climatic change through greenhouse gas emissions, and to land use change through climatic and socio-economic drivers, such as demand and technology. Four different general circulation models (GCMs) were used to simulate plausible changes in European climate (Mitchell et al. 2004).[7] The analysis was limited to seven priority scenarios out of all possible combinations of storylines and GCMs: A1f, A2, B1, B2 calculated with the GCM HadCM3 (variation across storylines, "socio-economic options"), and A2 calculated additionally with the GCMs CGCM2, CSIRO2 and PCM (variation across climate models, "climatic uncertainty"). All temperature change scenarios in Europe showed high regional variation, but a clear trend towards warming. The projected temperature increase in Europe ranged from 2.9 to 6.2ºC (across storylines) and from 3.0 to 5.2ºC for the A2 storyline (across GCMs; decadal average 2091-2100 compared to 1991-2000, Table 1). Changes in precipitation were more complex. In general, increases in winter precipitation and decreases in summer precipitation resulted in small overall changes when comparing annual averages (Table 1). Regional variation between the results of the climate models was considerable (Mitchell et al. 2004). Generally, all scenarios agreed in decreasing precipitation in the south of Europe, as well as mostly increasing precipitation in the north.

A set of future land use scenarios with the same spatial scale were developed based on the climatic and socio-economic scenarios (Ewert et al. 2004, Kankaanpää and Carter 2004, Reginster and Rounsevell 2005, Rounsevell et al. 2005a, Rounsevell et al. 2005b).[8] The

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[5] The time slices represent thirty-year averages; baseline 1990 (mean over 1961-1990), 2020 (mean over 1991-2020), 2050 (mean over 2021-2050) and 2080 (mean over 2051-2080).

[6] The Special Report of Emission Scenarios (SRES) are narrative descriptions of plausible future worlds that were developed by a large group of experts in a long-term open review process as a function of major driving forces, such as population growth, economic development and technological change (Nakicenovic and Swart 2000). They are structured in four major families labelled A1, A2, B1 and B2, each of which emphasises a different set of social, environmental and economic ideals. These ideals are organised along two axes. The first major dimension focuses on 'material consumption' (dimension A; also referred to as 'economically oriented'), versus 'sustainability, equity and environment', (dimension B; sometimes referred to as 'environmentally oriented'). The second major dimension distinguishes 'globalisation' (dimension 1) versus 'regionalisation' (dimension 2). The narratives specify typical aspects and processes for each of the four quadrants identified by these dimensions. The A1 scenario was further elaborated by assuming different combinations of fuels and technology development to satisfy energy demand. A1f remains dominated by fossil fuels. Trajectories of greenhouse gas emissions were quantified using the integrated assessment model IMAGE 2.2 (IMAGE team 2001). The A1f socio-economic scenario results in the highest emissions and consequently in the highest atmospheric concentrations of carbon dioxide (ca. 960 ppmv in 2100), followed by A2, B2 and finally B1 (870, 610 and 520 ppmv respectively; atmospheric CO_2 concentration in 2000 was ca 370 ppmv).

[7] Climate change scenarios with monthly values were created for five climatic variables: temperature, diurnal temperature range, precipitation, vapour pressure and cloud cover. The scenarios comprise all 16 combinations of four SRES emissions scenarios and four general circulation models (GCMs; PCM, CGCM2, CSIRO2, HadCM3), using GCM outputs from the IPCC Data Distribution Centre. The results were subsequently downscaled from 0.5°x0.5° to 10'x10' resolution. The climate scenarios of the 21st century replicate observed month-to-month, inter-annual and multi-decadal climate variability of the detrended 20th century climate. The full method is described in Mitchell et al. (2004). The scenarios are known as TYN SC 1.0 and are publicly available (an advanced version is available from the ATEAM project).

[8] The land use categories we distinguished were: urban, agriculture (cropland, grassland and biofuels), forestry and designated areas (for conservation or recreation goals) (Ewert et al. 2004, Kankaanpää and Carter 2004, Reginster and Rounsevell 2005, Rounsevell et al. 2005a, Rounsevell et al. 2005b). The approach recognised three levels in the derivation of land use scenarios that move from qualitative descriptions of global socio-

variation across land use scenarios based on different climate models, but on the same storyline was very small, indicating that socio-economic assumptions had a much greater effect on the land use scenario results than climatic drivers. The general trends shown by the land use scenarios were of reductions in agricultural areas for food production, partly compensated for by increases in bioenergy production and forests, as well as small increases in urban areas and areas protected for conservation and recreation (Table 1). In the A ("economically oriented") scenarios the decline in agricultural land was especially pronounced. Here decreases of up to 21% (absolute decrease in % of EU15+ area) in the surface areas of agricultural land used for food and fibre production (cropland and grassland) are caused primarily by the assumptions about the role of technological development (Ewert et al. 2005). Large parts of Europe become surplus to the requirement of food and fibre production, which allows extensification[9] and further provides opportunities for the substitution of food production by energy production through the cultivation of bioenergy crops (Rounsevell et al. 2005a).

Biomass energy production – Where to plant the power plants

The European Commission's White Paper for a Community Strategy proposed a target of doubling the contribution of renewable energy sources to 12% of the EU's total primary energy needs by 2010 (European Commission 1997). This has resulted in great interest of landowners, farmers and foresters in biomass energy production, as we learned early in our stakeholder dialogue. In direct response to stakeholders we have therefore investigated potential global change effects on the ecosystem service *biomass energy production*. We assessed the distribution of 26 potential bioenergy crops under changing climate conditions (Tuck et al. 2005).[10] Under all scenarios the potential distribution of temperate oilseed, cereals, starch crops and solid biofuels was projected to increase in northern Europe due to increasing temperatures (high latitudes, Table 1), and to decrease in the most southern areas due to increased drought (low latitudes, Table 1). Hence, in southern Europe the choice of bioenergy crops available will be reduced in future. Different crop types show different trends. For example, climate change will reduce the area suitable for barley, miscanthus, oilseed rape and potato in the latitudinal band 35-45 (Figure 2), while the climatic conditions seem to be improved for Sorghum. The climatic potential to grow barley, potato and oilseed

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economic storylines, over European sector driving forces, to quantitative projections of regional land use change. For each land use category the methodology broadly followed the same steps. First an assessment was made of the total area requirement (quantity) of each land use, as a function of changes in the relevant drivers. This was based on outputs from the global scale IMAGE 2.2 Integrated Assessment Model on commodity demands at the European scale (IMAGE team, 2001). Second, scenario-specific spatial allocation rules were developed and applied to locate these land use quantities in geographic space across Europe. Third and finally, the scenarios of the broad land use types were post-processed to maintain the land use constant in designated areas. This approach was implemented using a range of techniques that were specific to each land use type, including reviews of the literature, expert judgement, and modelling. Widespread consultation was undertaken with other experts in the field, as well as with stakeholders.

[9] We refer to extensification as the transition of a land cover or land use type associated with high intensity of use to a lower intensity of use (e.g. improved grassland to semi- natural cover).

[10] Bioenergy or biofuel crops are those annual and perennial species that are specifically cultivated to produce solid, liquid or gaseous forms of energy. Twenty-six actual or potential bioenergy crops were selected: oilseed rape, linseed, field mustard, hemp, sunflower, safflower, castor, olive, groundnut, barley, wheat, oats, rye, potato, sugar beet, jerusalem artichoke, sugarcane, cardoon, sorghum, kenaf, prickly pear, maize, reed canary grass, miscanthus, short rotation coppice, and eucalyptus. Simple rules were derived from the literature for each crop for suitable climate conditions and elevation. The climate conditions were based on minimum and maximum monthly temperatures at various times of the year, and precipitation requirements. All crops are assumed to be rain fed (not irrigated) and not protected from frost. The approach is described in detail in Tuck et al. (Tuck et al. 2005).

rape increased by 2080 in the Northern latitudes (Figure 2). Further agricultural considerations need to be taken into account when planning adaptive action based on these results, such as for example soil conditions.

Water supply – Growing population and *changing climate*

Reduced availability of water affects humans directly and indirectly, e.g. through effects on crop production. UNEP's Global Environment Outlook-3 as well as the World Resources Institute estimated increases in the numbers of people living in water-stressed basins, due entirely to population growth (World Resources Institute 2000, UNEP 2002). To assess the added constraint of climate change on water supply we used a macro-scale hydrological model (Mac-pdm: Arnell 1999 modified, Arnell 2003).[11] By 2080, climate change may increase the number of people living under water scarcity by up to 44.3 Million (Table 1). Reductions in 30-year mean runoff in parts of southern Europe may be as great as 30%. The adverse effect of this scarcity is exacerbated since extractions per capita are higher in southern Europe due to irrigation. Furthermore tourism results in substantial increases in water use, especially in summer. In addition to increasing the number of people served with water in a region, tourists' water consumption has been shown to be far in excess of that of local residents (World Tourism Organisation 2003). The variation in additional people living under water scarcity across different storylines (15.7-44.3 Million) was higher than across different GCMs (for A2: 5.8-15.7 Million, Table 1), stressing the potential to mitigate this impact by socio-economic changes.

Recreation – The winter tourism sector

Recreation is one of many cultural ecosystem service (Millennium Ecosystem Assessment 2003). It is difficult to find indicators for cultural ecosystem services, such as the recreational value of an area. However, winter tourism depends on reliable snow cover in the mountains. Therefore, indicators related to snow cover capture an essential feature of an area's value for winter recreation. A series of Alpine case studies.[12] indicated a rise in the elevation of reliable snow cover between 200 m and 400 m from about 1300 m today to 1500-1700 m at the end of the 21st century (Zierl and Bugmann 2005, Table 1 shows the figures for 2080). At present, about 85% of all Swiss ski areas have sufficient snow. A 300 m rise of the snow line would reduce this to about 63% (Elsässer and Messerli 2001). Stakeholders from the winter tourism industry already expect increased demand pressures on high altitude resorts. The World Tourism Organisation deems it "very probable" that ultimately the demand for winter sports will diminish (World Tourism Organisation 2003).

The change in snow cover will also change the seasonality of Alpine runoff. Rising temperatures will affect snow cover dynamics, enhancing winter stream flow, reducing

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[11] In general terms, the Mac-pdm model calculates the evolution of the components of the water balance at a daily time step (Arnell 1999 modified, Arnell 2003). Although the model was implemented at a scale of 10x10', for most of the analyses, runoff was aggregated to the 0.5°x0.5° scale. Döll and Lehner's (2002) drainage direction map was used to link the 0.5°x0.5° cells together and enable the accumulation of flows along the river network. A total of 94 major river basins have been identified, based on currently proposed river basins and major topographic boundaries. Basin areas ranged from just over 10,000 km^2 to 373,000 km^2.

[12] High-resolution case studies in Alpine catchments were performed for the Alptal, the Hirschbichl, the Dischma, the Saltina and the Verzasca catchment. An adapted version of the simulation system RHESSys (Tague and Band 2004) was used to estimate fluxes of water, carbon and nitrogen through the catchments. The model was adapted to Alpine conditions, particularly regarding maintenance respiration, phenology, snow accumulation and melting (Zierl et al. 2005).

summer stream flow by up to 46% and shifting monthly peak flows to earlier dates by up to two months (Zierl and Bugmann 2005).

Wood production

The total area of forest in Europe is projected to increase from 31% today to 32-37% of the EU15+ area in 2080 (Table 1). We assessed the effect of management, land use and climate change on wood production using the European forest model EFISCEN (Karjalainen et al. 2003).[13] In all scenarios, climate change was projected to result in increased forest growth, especially in Northern Europe and in the economically oriented scenarios (Table 1). The adverse effect of increased summer drought in Southern Europe was mitigated by higher precipitation in spring and increased water use efficiency in response to the rising atmospheric CO_2 concentrations. The increasing forest area led to increased increment because of a high proportion of young stands. When low wood demand (B scenarios) led to less intensive forest management, the age-class distribution of the forests shifted towards old and unproductive, and annual wood increment decreased by 10.0 % in the B1 scenario (in B2 afforestation counteracted this effect and led to an overall increase in increment by 9.7 %, Table 1). In general, management had a greater influence on the development of wood production than climate or land use change.

To obtain more detailed results on forest tree species in specific regions, we used a process-based model (GOTILWA+, Sabaté et al. 2002).[14] In general, the process-based simulations agreed with the positive trends in wood production. However, they indicated that some tree species would be affected negatively, especially in the longer term in the Mediterranean, due to increased drought. Furthermore, the risk of forest fires increased especially in the Mediterranean, primarily because of increased length of the fire season particularly in the dryer scenarios (e.g. those derived from HadCM3).[15] For example, the area burnt in the

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[13] EFISCEN is a large-scale forest scenario model that uses forest inventory data as input (Meyer et al. 2005). To incorporate climate change induced growth changes, net primary production values provided by the LPJ model (see below) were used to scale inventory based stem growth. Wood demand scenarios were derived from the IMAGE scenario documentation (IMAGE team 2001). The model projects possible future development of forests on a European, national or regional scale. The inventory data used in this study cover almost 100 million hectares of forest available for wood supply and reflect the state of the forest around the mid-1990 in 15 countries: EU15 without Greece and Luxembourg (due to the lack of suitable inventory data), plus Norway and Switzerland. Management regimes (age limits for thinnings and final fellings) were based on a country-level compilation of management guidelines. Forest management under these regimes is different in the different scenarios and depends on wood demand. When wood demand is high, management is intense (i.e. shorter rotation time length). Assumptions about which tree species would be chosen for afforestation were based on the socio-economic storylines. It was assumed that coniferous species would be favored in the A-scenarios, due to limited environmental concern and high wood demand. It was further assumed that only autochthonous tree species would be used for afforestation in the ‘environmentally oriented’ B-scenarios.

[14] GOTILWA+ (http://www.creaf.uab.es/gotilwa%2B/, Sabaté et al. 2002) is a detailed process-based model for managed and unmanaged forests implemented to simulate the forest growth processes under the influence of climate, tree and stand structure, management techniques and soil properties. Eco-physiological processes such as photosynthesis, transpiration, autotrophic and heterotrophic respiration are simulated in a daily time steps.

[15] The Dynamic Global Vegetation Model LPJ (Smith et al. 2001, Sitch et al. 2003) uses input on climate, soil and atmospheric CO_2 concentration to calculate carbon and water fluxes through vegetation and soil. The LPJ version used (Zaehle et al. 2005) has been adapted to account for cropland management and tracks anthropogenic land use changes over time, as well as natural and anthropogenic fires. The global dynamic vegetation model LPJ contains a regional fire module called Reg-FIRM (Thonicke et al. 2001, Venevsky et al. 2002). The model was modified to take into account all types of ecosystems within Europe. It explicitly considers human- and lightning-caused fires, climatic fire danger, and fire spread. Fire risk and wood area burnt depends on the following main factors: climate and weather, source of ignition, type of vegetation, amount of fuel, landscape structure, and fire fighting. Fire risk further depends on dynamic interactions between vegetation

Iberian Peninsula increased by up to 112% in 2080 for all but one scenario (Table 1). In general, biodiversity is expected to decline in the Mediterranean. In particular, the distribution of a number of Mediterranean tree species is likely to change, e.g. cork oak (*Quercus suber*), holm oak (*Q. ilex*), aleppo pine (*P. halepensis)* and maritime pine (*P. pinaster)*. This may be less important for wood production, but could have profound implications for the sense of place of the local inhabitants, the regional appearance, traditional forms of land use and the tourism sector.

Soil fertility maintenance

Besides being a key factor in the carbon cycle, soil organic matter content is important for maintaining soil fertility. We examined the impact of climate and land use change on soil organic carbon content in cropland, grassland and forest mineral soils using the Rothamsted Soil Carbon model (Smith et al. 2005a, Smith et al. 2005b).[16] Climate change alone decreased soil fertility in agricultural lands, but greater plant growth due to enhanced atmospheric carbon dioxide availability, climate and technological development reduced the extent of this adverse effect. In Europe, land use changes, particularly abandonment of agriculture partly counteracted the adverse climate effect on total soil organic carbon content. Afforestation led to a net increase in soil organic carbon in forest soils, despite the climate-induced increases in soil respiration (Table 1). These results alone cannot estimate the risk of European arable land becoming dust bowls as in the example of the Palliser Triangle above. However, they draw attention to the fact that soil respiration can counteract increased primary production. Sustainable soil management is key to the supply of a number of ecosystem services, for example agricultural production and climate regulation.

European vulnerability

The results of the European vulnerability assessment, of which some have been briefly presented here, represent a plausible range of impacts to be expected. The uncertainty inherent in these estimates is large. Nevertheless, the direction of some problematic trends is common in all scenarios. Though some of these trends may be considered positive (e.g. increases in forest area and productivity), and others hold potential future opportunities (e.g. "surplus land" for agricultural extensification and biomass energy production), most impacts are projected to have negative consequences for society (e.g. declining soil fertility, increasing risk of forest fires). These environmental impacts will add to our vulnerability to global change.

In comparison between European regions, the Mediterranean seems most vulnerable within Europe. Multiple potential impacts, related primarily to increased temperatures and reduced precipitation, on multiple sectors were projected. These include water shortages especially in the summer months when demand peaks due to tourism, increased fire risk in the forestry

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and fire. On the one hand, CO_2 fertilization might dampen fire risk due to increased water use efficiencies of plants, thereby reducing the demand for water uptake from the soil and increasing litter moisture. On the other hand, climate-induced shifts in vegetation, associated with changes in fuel characteristics, can amplify fire spread (Thonicke and Cramer 2004).

[16] Further input for the Rothamsted Carbon model (Coleman et al. 1997) were the best available soils data (European Soils Database), historic land use reconstructions for the 20th century, as well as outputs on potential evapotranspiration (water loss from the soil and the plant), net primary production from the LPJ model (see above), as well as litter fall in forests from EFISCEN (see above). The model was used to simulate soil organic carbon content of mineral soil (< 200 t C ha^{-1}) down to 30 cm depth. See Smith et al. (Smith et al. 2005a, Smith et al. 2005b) for further details.

sector, losses in the carbon storage potential (not discussed here), northward shifts in the distribution of tree species like maritime pine and cork oak, and losses of agricultural potential due to drought. In the Mediterranean these potential impacts combine with socio-economic development that hints lower adaptive capacity[17] in comparison to other European regions.

The active participation and sustained interest of our collaborating stakeholders show that global change is an issue of concern to them, albeit among many others. The final product of the European assessment is a digital atlas of maps of changing ecosystem service supply and vulnerability (Metzger et al. 2004). Stakeholders have commented on the usefulness of the assessment with encouragement and criticism alike (Schröter et al. 2004a, De la Vega-Leinert and Schröter 2005). They were considerably more interested in information on ecosystem services and potential changes in supply than in generic indicators for adaptive capacity or vulnerability. To increase the usefulness of our results, even finer spatial and temporal scales will have to be tackled. Interactions between sectors and services have to be taken into account more fully.

Lowering vulnerability through sustainable management of ecosystem services

The basis for resilient, i.e. not vulnerable, human-environment systems is the sustainable use of ecosystem services without compromising one vital service over another. Ecosystem services can be private goods, such as the provisioning service timber production on privately owned land. However, the very same forest system also provides other ecosystem services, for example, the supporting service primary production, the regulating service climate regulation, and the cultural service aesthetic appeal. These services are public goods, whether recognised as such or not. The concept of ecosystem services holds the advantage that these private and public goods can be identified, acknowledged and managed as vital connections between ecosystems and humans in a more systematic way. There seem to be three main reasons for unsustainable management of ecosystem services, one or more of which may apply in a particular case:

1. An ecosystem service is not recognised.
2. An ecosystem service is compromised to maximise profits at the cost of the public, because regulation and taxation set no limits.
3. An ecosystem service is used unsustainably, because of an immediate vital need and no alternatives.

The pollinator example described above may be a case of the first reason. Though certainly recognised by farmers, pollination was probably long taken for granted by most people – leading to the publication of a book with the meaningful title *The Forgotten Pollinators* (Buchmann and Nabhan 1996).

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[17] We used the SRES based socio-economic scenarios to develop a spatially explicit and quantitative index of adaptive capacity (macro-scale: province level), based on six determinants: power, flexibility, freedom, motivation, knowledge and urgency. For these determinants we selected twelve indicators such as gross domestic product, female activity rate, age structure, literacy index and urbanisation. Fuzzy inference rules were then applied to aggregate the individual indicator values into one measure of adaptive capacity per spatial unit. The resulting generic index captures one of many dimensions of adaptive capacity. The index does not take into account the likely transfers of capital within the EU to poorer regions. Since there is no way of validating this approach to adaptive capacity, results should be treated as hypothetical.

Examples for the second case seem countless: exploiting one ecosystem service to the benefit of one actor, but to the cost of the public due to lack of regulation. This is known in game theory as the “free-rider problem”. The complexity of the human-environment system leaves room for many free rides (Houck 2003). The most obvious example may be using the atmosphere as a dump for greenhouse gases and thereby altering the global climate, which is likely to alter the majority of ecosystem services, as described in the European case study above.

The underlying cause of the Canadian dust bowl might be seen as farmers’ immediate need to make a living, the third reason for unsustainable use of an ecosystem service. Soil erosion has accompanied human life on earth in three big waves, each of which was followed by management efforts (McNeill and Winiwarter 2004). Another example can be taken from the poorest country of the Western Hemisphere, namely Haiti. Haiti has undergone rapid deforestation, to increase arable area on marginal lands and to extract firewood. This was caused by the dire need of an extremely poor population that is not entitled to use the low-lying fertile lands. Only 20% of the land is considered arable, however 50% is currently under agricultural production (FAO 2001). Today less than 2% of the land is forested. Deforestation has destabilised soils and altered the river basins, leading to soil erosion and increased risk of floods. In May 2004, heavy rains caused flooding and mudslides, killing 2665 people (EM-DAT 2005). Only four months later, hurricane Jeanne brought heavy rainfalls and caused yet another devastating flood killing 2745 more people in Gonaïves, Haiti’s third largest city, where hardly a house was left untouched by the flood waters (EM-DAT 2005). While deforestation is widely acknowledged as a main cause of these disasters, reforestation is a slow and tedious task. Haiti is politically unstable and struggles for elections against violent outbreaks.

How can environmental science facilitate sustainable management of ecosystem services, and consequently decrease vulnerability? The first obligation is to raise awareness of the importance and complexity of ecosystems and the services they provide. In this respect, the Millennium Ecosystem Assessment (MA, www.millenniumassessent.org) has been a tremendous achievement. The MA was a global ecosystem study that represents a consensus of over 1300 scientists. One of its four key findings was that *“[t]he degradation of ecosystem services could grow significantly worse during the first half of this century and is a barrier to achieving the Millennium Development Goals”* (Reid et al. 2005). However, further studies are needed that specify and quantify the supply of ecosystem services under different management option, such as for example the European assessment described above (Schröter et al. 2004a).

If an ecosystem service is compromised to maximise profits at the cost of the public, because regulation and taxation set no limits, environmental scientists can sound the alarm and shed light on the causality. Research unravels how different ecosystem services work together. Ecosystem models can translate climate and land use changes into changes in ecosystem service supply. One of the key ingredients to optimal use of ecosystem services is a reliable model of the ecosystem’s response to different forms of use (Scheffer et al. 2000). Therefore, ecosystem models need to incorporate human actors and management. However, we neither have complete understanding nor control of the human-environment system. Scientists and policy makers have to work together to find useful regulations in the face of uncertainty. This leaves room for ill-willed manipulation, such as exaggerating the uncertainty of a finding to get away with complacency. For example, some ignore the consensus on anthropogenic climate change to avoid measures to reduce greenhouse gas emissions (Oreskes 2004). How can society ensure that scientific knowledge and its limits are represented adequately to serve its people best? How can we ensure free media, an alert and well-informed public, as well as candid scientists and policy makers?

Finally, if ecosystem services are compromised to fulfil an immediate vital need, environmental scientists can ideally offer alternative and more sustainable technologies based on an understanding of the ecosystem. The implementation of alternative technologies itself requires social, economic and environmental resources. Therefore the key question remains: How to entitle and empower the poor to use their environment sustainably?

Conclusions

Human well-being depends on the sustained supply of ecosystem services – unsustainable use of ecosystem services increases vulnerability. Environmental scientists alone cannot provide the information and the tools that are needed to lessen the vulnerability of a region. However, they can make an essential contribution. They identify ecosystem services as vital links between humans and ecosystems. Moreover, they provide the best current understanding of the dynamics of the complex ecosystems that supply these services. Ecosystem models that include human management play an essential role in integrated assessment of global change. The uncertainty inherent in scientific knowledge leaves room for ill-willed manipulation. A sustained active dialogue between a free media, an alert and well-informed public, candid scientists and policy makers seems to be the best insurance against this. Sustainable management of ecosystem services thus requires abundant social, economic and environmental resources. Therefore the key question remains: How to entitle and empower the poor to use their environment sustainably? This is a question that will not be answered by environmental scientists alone. It is the fundamental puzzle of humanity.

Literature cited

Arnell, N. W. 1999. A simple water balance model for the simulation of streamflow over a large geographic domain. Journal of Hydrology **217**:314-335.

Arnell, N. W. 2003. Effects of IPCC SRES emissions scenarios on river runoff: a global perspective. Hydrology and Earth System Sciences **7**:619-641.

Buchmann, S. L., and G. P. Nabhan. 1996. The Forgotten Pollinators. Island Press, Washington D.C.

Cohen, J. E. 2003. Human Population: The Next Half Century. Science **302**:1172.

Coleman, K., D. Jenkinson, G. Crocker, P. Grace, J. Klir, M. Körschens, P. Poulton, and D. Richter. 1997. Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. Geoderma **81**:29-44.

Daily, G. C. 1997. Nature's services. Island Press / Shearwater Books, Washington.

Daily, G. C., and K. Ellison. 2002. The new economy of nature - The quest to make conservation profitable. Island Press / Shearwater Books, Washington.

de Groot, R. S. 1992. Functions of Nature: evaluation of nature in environmental planning, management and decision-making. Wolters-Noordhoff BV, Groningen, The Netherlands.

De la Vega-Leinert, A. C., and D. Schröter. 2005. The 3rd ATEAM stakeholder dialogue workshop – Vulnerability of human sectors to global changes. Pages 59 *in* May 3-4 2004, Potsdam, Germany,.

Döll, P., and B. Lehner. 2002. Validation of a new global 30-minute drainage direction map. Journal of Hydrology **258**:214-231.

Elsässer, H., and P. Messerli. 2001. The vulnerability of the snow Industry in the Swiss Alps. Mountain Research and Development **21**:335-339.

EM-DAT. 2005. Emergency Disasters Data Base. http://www.em-dat.net/who.htm.

European Commission. 1997. Energy for the Future: Renewable Sources of Energy -- White Paper for a Community Strategy and Action Plan. 599, European Communities, Luxembourg.

Ewert, F., M. D. A. Rounsevell, I. Reginster, M. Metzger, and R. Leemans. 2004. (in press) Technology development and climate change as drivers of future agricultural land use. *in* B. McCarl, editor. Rural lands, agriculture and climate beyond 2015: Usage and management responses. Kluwer Academic Publishers.

Ewert, F., M. D. A. Rounsevell, I. Reginster, M. J. Metzger, and R. Leemans. 2005. Future scenarios of European agricultural land use I. Estimating changes in crop productivity. Agriculture Ecosystems & Environment **107**:101-116.

Falkenmark, M., J. Lundquist, and C. Widstrand. 1989. Macro-scale water scarcity requires micro-scale approaches: aspects of vulnerability in semi-arid development. Natural Resources Forum **13**:258-267.

FAO. 2001. The State of Food and Agriculture 2001. *in*. Food and Agriculture Organization of the United Nations (FAO).

Fraser, E. D. G. 2003. Social vulnerability and ecological fragility: Building bridges between social and natural sciences using the Irish Potato Famine as a case study. Conservation Ecology **7**.

Gunderson, L., C. S. Holling, and S. S. Light. 1995. Barriers and bridges to the renewal of ecosystems and institutions. Columbia University Press, New York.

Holden, C. 2004. Consider the pollinators. Science **304**:1592.

Holling, C. S. 2001. Understanding the complexity of economic, ecological, and social systems. Ecosystems **4**:390-405.

Houck, O. 2003. Tales from a troubled marriage: Science and law in environmental policy. Science **302**:1926-1929.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson. 2001. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) -- Climate Change 2001: The Scientific Basis. Cambridge University Press.

IMAGE team. 2001. The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate change and impacts in the 21st century. *in*. National Institute of Public Health and the Environment (RIVM), Bilthoven, The Netherlands.

Ingram, M., G. Nabhan, and S. L. Buchmann. 1996. Our fogotten pollinators: Protecting the birds and bees. PANNA - Pesticide Action Network North America **6**.

IPCC. 2001. Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report. Climate Change 2001: The Scientific Basis; Impacts, Adaptation & Vulnerability; Mitigation. Cambridge University Press.

Kankaanpää, S., and T. R. Carter. 2004. Construction of European forest land use scenarios for the 21st century. Finnish Environment Institute, Helsinki.

Karjalainen, T., A. Pussinen, J. Liski, G.-J. Nabuurs, T. Eggers, T. Lapveteläinen, and T. Kaipainen. 2003. Scenario analysis of the impacts of forest management and climate change on the European forest sector carbon budget. Forest Policy and Economics **5**:141-155.

Kremen, C., N. M. Williams, R. L. Bugg, J. P. Fay, and R. W. T. 2004. The area requirements of an ecosystem service: crop pollination by native bee communities in California. Ecology Letters **7**:1109-1119.

McNeill, J. R. 2001. Something new under the sun: An environmental history of the twentieth-century world. W.W. Norton & Company Inc., New York, NY, USA.

McNeill, J. R., and V. Winiwarter. 2004. Breaking the Sod: Humankind, History, and Soil. Science **304**:1627-1629.

Metzger, M., and D. Schröter. 2005 (in review). Concept for a spatially explicit and quantitative vulnerability assessment of Europe. Regional Environmental Change.

Metzger, M. J., R. Leemans, D. Schröter, W. Cramer, and ATEAM consortium. 2004. The ATEAM vulnerability mapping tool. Office C.T. de Wit Graduate School for Production Ecology & Resource Conservation (PE&RC), Wageningen, The Netherlands.

Meyer, J., M. Lindner, S. Zudin, and et al. 2005. (in review) Forest resource development in Europe under changing climate and land use. Global Change Biology.

Millennium Ecosystem Assessment. 2003. Ecosystems and Human Well-being: a framework for assessment -- Millennium Ecosystem Assessment. Island Press, Washington.

Mitchell, T. D., T. R. Carter, P. D. Jones, M. Hulme, and M. New. 2004. A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100). Tyndall Centre for Climate Change Research Working Paper **55**:25.

Moss, R., A. Brenkert, and E. L. Malone. 2000. Measuring Vulnerability: A Trial Indicator Set. *in*. Pacific Northwest Laboratories.

Nabhan, G. P., and S. L. Buchmann. 1997. Services provided by pollinators. Pages 133-150 *in* G. C. Daily, editor. Nature's Services: Societal Dependence on Natural Ecosystems. Island Press, Washington D.C.

Nakicenovic, N., and R. Swart, editors. 2000. IPCC Special Report on Emissions Scenarios (SRES). Cambridge University Press, Cambridge, U.K.

Oberthur, A. 2004. Almond growers scramble for pollinating honey bees. Indiana State Beekeepers Association Journal **124**:8.

Oreskes, N. 2004. The scientific consensus on climate change. Science **306**:1686.

Palmer, M., E. Bernhardt, E. Chornesky, S. Collins, A. Dobson, C. Duke, B. Gold, R. Jacobson, S. Kingsland, R. Kranz, M. Mappin, M. L. Martinez, F. Micheli, J. Morse, M. Pace, M. Pascual, S. Palumbi, O. J. Reichmann, A. Simons, A. Townsend, and M. Turner. 2004. Ecology for a crowded planet. Science **304**:1251-1252.

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

Reginster, I. R., and M. D. A. Rounsevell. 2005. Future scenarios of urban land use in Europe. Environ. Plan. B. **(submitted)**.

Reid, W. V., H. A. Mooney, A. Cropper, D. Capistrano, S. R. Carpenter, K. Chopra, P. Dasgupta, T. Dietz, A. K. Duraiappah, R. Hassan, R. Kasperson, R. Leemans, R. M. May, T. A. J. McMichael, P. Pingali, C. Samper, R. Scholes, R. T. Watson, A. H. Zakri, Z. Shidong, N. J. Ash, E. Bennett, P. Kumar, M. J. Lee, C. RaudseppHearne, H. Simons, J. Thonell, and M. B. Zurek. 2005. Millennium Ecosystem Assessment Synthesis Report. Island Press, Washington DC.

Root, T. L., J. T. Price, K. R. Hall, S. H. Schneider, C. Rosenzweig, and J. A. Pounds. 2003. Fingerprints of global warming on wild animals and plants. Nature **421**:57-60.

Rounsevell, M. D. A., F. Ewert, I. Reginster, R. Leemans, and T. R. Carter. 2005a. Future scenarios of European agricultural land use II. Projecting changes in cropland and grassland. Agriculture Ecosystems & Environment **107**:117-135.

Rounsevell, M. D. A., I. Reginster, M. B. Araújo, T. R. Carter, N. Dendoncker, F. Ewert, J. I. House, S. Kankaanpää, R. Leemans, M. J. Metzger, C. Schmit, P. Smith, and G. Tuck. 2005b. A coherent set of future land use change scenarios for Europe. Agriculture Ecosystems & Environment (submitted).

Sabaté, S., C. A. Gracia, and A. Sánchez. 2002. Likely effects of climate change on growth of *Quercus ilex*, *Pinus halepensis*, *Pinus pinaster*, *Pinus sylvestris* and *Fagus sylvatica* forests in the Mediterranean region. Forest Ecology & Management **162**:23-37.

Sala, O. E., F. S. Chapin, J. J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L. F. Huenneke, R. B. Jackson, A. Kinzig, R. Leemans, D. M. Lodge, H. A. Mooney, M. Oesterheld, N. L. Poff, M. T. Sykes, B. H. Walker, M. Walker, and D. H. Wall. 2000. Biodiversity - Global biodiversity scenarios for the year 2100. Science **287**:1770-1774.

Scheffer, M., W. Brock, and F. Westley. 2000. Socioeconomic mechanisms preventing optimum use of ecosystem services: An interdisciplinary theoretical analysis. Ecosystems **3**:451-471.

Schröter, D. 2001. Assessing vulnerability of European ecosystem services. *in* Methods and Models of Vulnerability Research, Analysis and Assessment, Potsdam, Germany.

Schröter, D., L. Acosta-Michlik, A. W. Arnell, M. B. Araújo, F. Badeck, M. Bakker, A. Bondeau, H. Bugmann, T. Carter, A. C. d. l. Vega-Leinert, M. Erhard, G. Z. Espiñeira, F. Ewert, U. Fritsch, P. Friedlingstein, M. Glendining, C. A. Gracia, T. Hickler, J. House, M. Hulme, S. Kankaanpää, R. J. T. Klein, B. Krukenberg, S. Lavorel, R. Leemans, M. Lindner, J. Liski, M. J. Metzger, J. Meyer, T. Mitchell, F. Mohren, P. Morales, J. M. Moreno, I. Reginster, P. Reidsma, M. Rounsevell, E. Pla, J. Pluimers, I. C. Prentice, A. Pussinen, A. Sánchez, S. Sabaté, S. Sitch, B. Smith, J. Smith, P. Smith, M. T. Sykes, K. Thonicke, W. Thuiller, G. Tuck, G. v. d. Werf, J. Vayreda, M. Wattenbach, D. W. Wilson, F. I. Woodward, S. Zaehle, B. Zierl, S. Zudin, and W. Cramer. 2004a. ATEAM (Advanced Terrestrial Ecosystem Analyses and Modelling) Final Report. Potsdam Institute for Climate Impact Research (PIK), Potsdam.

Schröter, D., M. J. Metzger, W. Cramer, and R. Leemans. 2004b. Vulnerability assessment -- analysing the human enviornment system in the face of global environmental change. Environmental Science Section Bulletin **2**:11-17.

Schröter, D., C. Polsky, and A. G. Patt. 2005 (in press). Assessing vulnerabilities to the effects of global change: an eight step approach. Mitigation and Adaptation Strategies for Global Change.

Sitch, S., B. Smith, I. C. Prentice, A. Arneth, A. Bondeau, W. Cramer, J. O. Kaplan, S. Levis, W. Lucht, M. T. Sykes, K. Thonicke, and S. Venevsky. 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Global Vegetation Model. Global Change Biology **9**:161-185.

Smith, B., I. C. Prentice, and M. T. Sykes. 2001. Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. Global Ecology and Biogeography **10**:621-637.

Smith, J. U., P. Smith, M. Wattenbach, S. Zaehle, R. Hiederer, R. J. A. Jones, L. Montanarella, M. D. A. Rounsevell, I. Reginster, and F. Ewert. 2005a. Projected changes in mineral soil carbon of European croplands and grasslands, 1990-2080. Global Change Biology (in review).

Smith, P., J. U. Smith, M. Wattenbach, J. Meyer, M. Lindner, S. Zaehle, R. Hiederer, R. Jones, L. Montanarella, M. Rounsevell, I. Reginster, and S. Kankaanpää. 2005b. Projected changes in mineral soil carbon of European forests, 1990-2100. Canadian Journal of Soil Science (in press).

Smith, P., S. Zaehle, E. Milne, M. Wattenbach, J. U. Smith, J. Meyer, M. Lindner, R. Hiederer, R. Jones, L. Montanarella, M. Rounsevell, I. Reginster, S. Kankaanpää, and F. Ewert. 2005c. (In preparation) Changes in total soil carbon in Europe, 1990-2080 using two models. Global Biogeochemical Cycles.

Smith, V. H., G. D. Tilman, and J. C. Nekola. 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environmental Pollution **100**:179-196.

Stenseth, N. C., A. Mysterud, G. Ottersen, J. W. Hurrell, K.-S. Chan, and M. Lima. 2002. Ecological Effects of Climate Fluctuations. Science **297**:1292-1296.

Tague, C., and L. Band. 2004. RHESSys: Regional hydro-ecologic simulation system: An object-oriented approach to spatially distributed modelling of carbon, water and nutrient cycling. Earth Interactions **8**:1-42.

Thonicke, K., and W. Cramer. 2004. (in press) Long-term trends in vegetation dynamics and forest fire in Brandenburg (Germany) under a changing climate. Natural Hazards.

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

Tuck, G., M. J. Glendining, P. Smith, J. I. House, and M. Wattenbach. 2005. (submitted) The potential distribution of bioenergy crops in Europe under present and future climate. Global Change Biology.

Turner, B. L., R. E. Kasperson, P. A. Matson, J. J. McCarthy, R. W. Corell, L. Christensen, N. Eckley, J. X. Kasperson, A. Luers, M. L. Martello, C. Polsky, A. Pulsipher, and A. Schiller. 2003. A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences of the United States of America **100**:8074-8079.

UNEP. 2002. GEO-3: Global Environmental Outlook Report 3. UNEP - United Nations Environment Programme.

van der Leeuw, S. E. 2001. 'Vulnerability' and the Integrated Study of Socio-natural Phenomena. Update - Newsletter of the International Human Dimensions Programme on Global Environmental Change **2**:Article 2.

Venevsky, S., K. Thonicke, S. Sitch, and W. Cramer. 2002. Simulating fire regimes in human-dominated ecosystems: Iberian Peninsula case study. Global Change Biology **8**:984-998.

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

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

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

Watson, R. T., I. R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verardo, and D. J. Dokken, editors. 2000. Land Use, Land-Use Change And Forestry. A Special Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, UK.

Watson, R. T., and the Core Writing Team, editors. 2001. Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK and New York, NY, USA.

World Resources Institute. 2000. World Resources 2000–2001. People and Ecosystems: The Fraying Web of Life. World Resources Institute, Washington.

World Tourism Organisation. 2003. Climate Change and Tourism. Pages 55 *in* The 1st International Conference on Climate Change and Tourism, Djerba, Tunisia.

Zaehle, S., A. Bondeau, P. Smith, and et al. 2005. (in prep.) Projected changes in terrestrial carbon storage in Europe under climate and land-use change, 2000-2100. Regional Environmental Change.

Zierl, B., and H. Bugmann. 2005. Global change impacts on hydrological processes in Alpine catchments. Water Resources Research **41**:WO2028.

Zierl, B., H. Bugmann, and C. L. Tague. 2005. (submitted) Evaluation of water and carbon fluxes in the ecohydrological model RHESSys.

Tables and Figures

Table 1. Summary of main trends in drivers and impacts for Europe during this century.

Figure 1. The role of ecosystems in assessments of global change effects on human welfare. **A.** Traditional view (Moss et al. 2000, IPCC 2001). **B.** View emerging from the concept of ecosystem services (Schröter et al. 2004b, Metzger and Schröter 2005 (in review)). Figure modified from Schröter (2001).

Figure 2. Change in potential area for growth in different latitudinal bands in Europe in 2080 compared to baseline (1990) in percent (%). This change is due to changes in climatic conditions only, soil conditions are not taken into account. Results provided by Margaret Glendening and Gill Tuck, Institute of Arable Crops Research, Rothamsted, UK.

Table 1. Summary of main trends in drivers and impacts for Europe during this century.

Storyline	A1f	A2	A2	A2	A2	B1	B2
GCM	HadCM3	HadCM3	PCM	CGCM2	CSIRO	HadCM3	HadCM3
Temperature change (ºC)[a]	6.2	5.2	3.0	4.0	4.7	2.9	3.4
Annual average precipitation change (%)[b]	-2	-1	3	2	6	-2	-1
Land use change (%)[c]							
Cropland (for food production)	-10.7	-10.4	-10.6	-10.7	-10.6	-7.0	-6.4
Grassland (for lifestock)	-8.7	-10.0	-10.1	-10.2	-10.0	-1.1	-6.7
Forest	0.8	0.7	1.0	1.0	1.2	3.5	5.6
Urban	0.09	0.08	0.07	0.07	0.07	0.05	0.06
Biofuel production	8.7	8.7	9.1	8.6	8.6	3.4	7.4
Protected	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Surplus	9.8	10.9	10.5	11.2	10.8	1.1	0.0
Pot. distribution change, biofuels (%)[d]							
Overall	1	3	6	7	5	3	4
Latitude 35-45	-13	-8	-1	-3	-2	-7	-6
Latitude 45-55	-6	-2	4	8	-6	-1	0
Latitude 55-65	12	13	11	14	15	12	13
Latitude 65-71	32	23	19	16	34	18	22
Additional people living under water scarcity (10^6)[e]	44.3	15.7	7.5	11.7	5.8	44.3	25.8
Change elevation of reliable snow cover (m)[f]	450	310	200	230	390	230	180
Change in wood increment (%)[g]	3.8	4.4	2.9	2.9	6.2	-10.0	9.7
Change in area burnt, Iberian Peninsula (%)[h]	80	55	-1	37	8	112	57
Change in soil organic carbon (Pg C)[i]							
Total	-4.1	-4.4	-4.3	-4.5	-4.8	-0.1	-0.9
Cropland	-5.9	-5.6	-5.4	-5.5	-5.8	-4.3	-4.3
Grassland	-2.2	-2.7	-2.7	-2.7	-2.8	1.5	-1.2
Forest	1.0	1.1	1.3	1.3	0.7	2.8	3.6

[a] Temperature, average 2091-2100 compared to average 1991-2000 (Mitchell et al. 2004).

[b] Annual average precipitation, average 2091-2100 compared to average 1991-2000 (Mitchell et al. 2004). The changes seem small, since seasonal variation (increases in winter, decreases in summer) tend to level each other out in annual averages.

[c] Land use area (%), 2080 compared to baseline (Ewert et al. 2004, Kankaanpää and Carter 2004, Reginster and Rounsevell 2005, Rounsevell et al. 2005a, Rounsevell et al. 2005b). Baseline areas (% of EU15+): cropland 23.0 %, grassland 17.2 %, forest 31.0 %, urban 1.5 %, other (shrubland, barren land, wetland, inland waters, sea, permanent ice and snow) 27.3 %.

[d] Change in potential distribution of 26 biofuel crops due to climate change, land area (%), 2080 compared to baseline (Tuck et al. 2005).

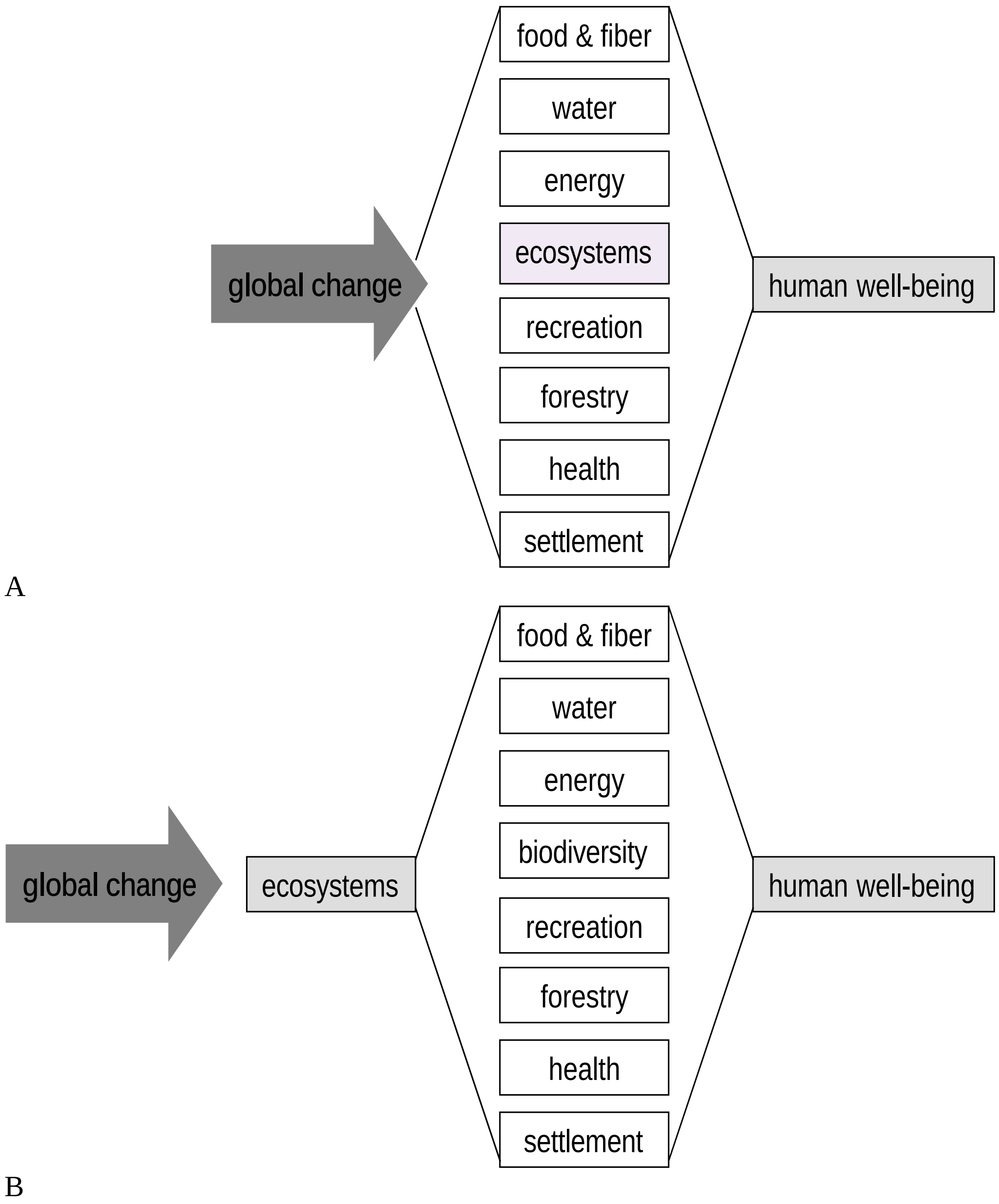
[e] Additional people (millions) living in watersheds with less than 1700 $m^3 capita^{-1} year^{-1}$ due to climate change in 2080 (compared with hypothetical case of no climate change). Water-related resource problems are likely when water availability per capita falls below the threshold of 1700 m^3 $capita^{-1} year^1$ (Falkenmark et al. 1989).

[f] Change in elevation of reliable snow cover (m), 2080 compared to baseline. Average from five Alpine case studies (Zierl and Bugmann 2005).

[g] Change in wood increment (%), 2080 compared to baseline (Meyer et al. 2005).

[h] Change in area burnt in the Iberian Peninsula (%), 2080 compared to baseline.

[i] Change in cumulative soil organic carbon content in mineral soil down to 30 cm depth (Pg C), 2080 compared to baseline; total (Smith et al. 2005c), cropland and grassland (Smith et al. 2005a), and forest (Smith et al. 2005b).



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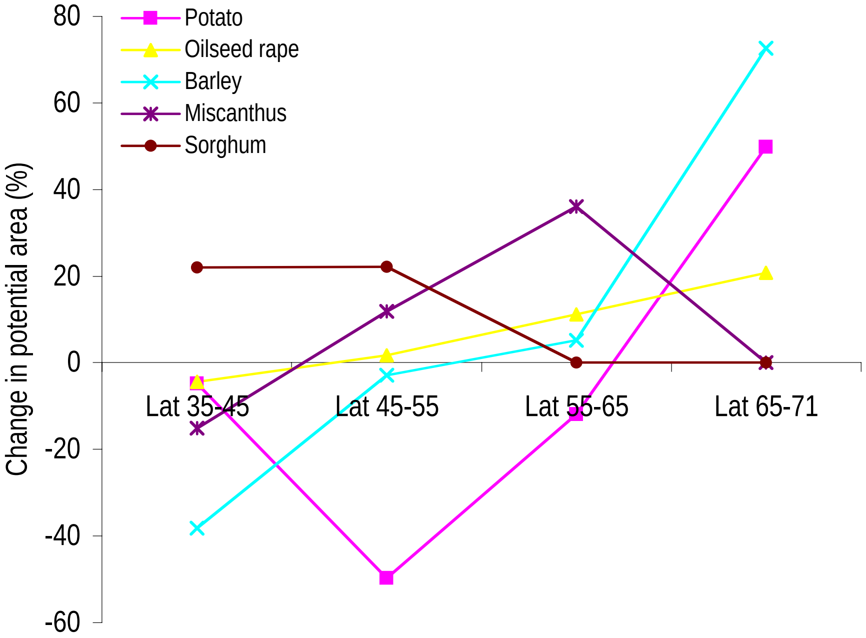

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