Global Ecology and Biogeography, (Global Ecol. Biogeogr.) (2012) **21**, 5–18

Global Ecology and Biogeography
A Journal of Macroecology

SPECIAL ISSUE

Scenarios for investigating risks to biodiversity

Joachim H. Spangenberg[1,2]*, Alberte Bondeau[3], Timothy R. Carter[4], Stefan Fronzek[4], Jill Jaeger[5], Kirsti Jylhä[6], Ingolf Kühn[1], Ines Omann[5], Alex Paul[7], Isabelle Reginster[8]†, Mark Rounsevell[9], Oliver Schweiger[1], Andrea Stocker[5], Martin T. Sykes[10] and Josef Settele[1]

[1]*UFZ, Helmholtz Centre for Environmental Research, Department of Community Ecology, Theodor-Lieser-Strasse 4, 06120 Halle/Saale, Germany,* [2]*Sustainable Europe Research Institute SERI Germany e.V., Vorsterstrasse 97-99, 51103 Cologne, Germany,* [3]*Potsdam Institute for Climate Change Research, Telegrafenberg, PO Box 60 12 03, D-144 12 Potsdam, Germany,* [4]*Finnish Environment Institute (SYKE), Box 140, Mechelininkatu 34a, FI-00251 Helsinki, Finland,* [5]*SERI Sustainable Europe Research Institute GmbH, Garnisongasse 7/21, A-1090 Vienna, Austria,* [6]*Finnish Meteorological Institute, Climate Research and Applications, PO Box 503, FI-00101 Helsinki, Finland,* [7]*Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK,* [8]*UCL – Department of Geography, Place Pasteur, 3, B- 1348 Louvain-la-Neuve, Belgium,* [9]*Centre for the Study of Environmental Change and Sustainability, School of Geosciences, University of Edinburgh, Drummond Street, Edinburgh EH8 9XP, UK,* [10]*Department of Earth and Ecosystem Sciences, Lund University, Sölvegatan 12, 223 62 Lund, Sweden*

*Correspondence: Joachim H. Spangenberg, Sustainable Europe Research Institute SERI Germany e.V., Vorsterstrasse 97-99, 51103 Cologne, Germany.
E-mail: Joachim.Spangenberg@gmx.de
†Present address: IWEPS – Institut Wallon de l'Evaluation, de la Prospective et de la Statistique, Rue Fort de Suarlée, 1, B-5001 Namur, Belgium.

ABSTRACT

Aim This paper describes a set of integrative scenarios developed in the ALARM (Assessing LArge-scale environmental Risks for biodiversity with tested Methods) project. The ultimate aim of ALARM was to develop and test methods and protocols for the assessment of large-scale environmental risks to biodiversity and to evaluate mitigation options. Scenarios provide a tool for exploring such risks and the policy options to mitigate them; therefore they play a central role within the ALARM project.

Methods Three integrative scenarios (liberalization, business as might be usual, sustainability) were developed and illustrated using the econometric model described in a subsequent paper. They are contextualized with projections from climate models and provide the input for model-based assessments of biodiversity trends. Additionally, three shock scenarios were developed (Gulf Stream collapse, peak oil, pandemic) to demonstrate the limits of linear extrapolation. As these extend beyond model capabilities, they are discussed semi-quantitatively based on modelling insights.

Results Although the policy impacts on biodiversity are different for different pressures, biomes and species groups, some general trends could be identified. An extension of current EU policies will act as a brake on current trends by slowing down the loss of biodiversity in many cases and in most biomes, but it will be capable of neither halting nor of reversing the loss. Liberalization has the effect of accelerating biodiversity loss across the board, with few exceptions. A coherent sustainability scenario is clearly the most effective at preserving biodiversity, but the variant tested here still does not halt losses in all cases.

Main conclusions Current EU policies for protecting biodiversity appear to be insufficient to reverse ongoing losses. Coherent sustainability strategies are effective at conserving biodiversity, but in order to assess losses and then reverse them, measures would need to be introduced that extend beyond the steps tested in the ALARM sustainability scenario.

Keywords
Biodiversity, uncertainty, integration, policy implications, scenarios, storylines.

THE CONTEXT

ALARM (Assessing LArge-scale environmental Risks for biodiversity with tested Methods) was an Integrated Project (IP) within the Sixth Framework Programme of the European Commission (EC). The ultimate aim of the ALARM project was to develop and test methods and protocols for the assessment of large-scale environmental risks (Settele *et al.*, 2005; see also http://www.alarmproject.net). To do so, ALARM integrated the research results of more than 250 scientists from 68 institutions

DOI: 10.1111/j.1466-8238.2010.00620.x
http://wileyonlinelibrary.com/journal/geb

in 35 countries. These results have formed the basis of policy recommendations in an attempt to support evidence-based decision making on biodiversity-relevant issues.

In the ALARM project, scenarios have been used as an integrative and prospective tool. Three base and three shock scenarios were developed. They accumulate knowledge from different disciplines in an attempt to make it more comprehensible and thus more useful to the policy process than raw scientific measurement data or direct model outputs could be.

The challenge

One peculiarity of the ALARM project is that it goes beyond existing assessments of biodiversity risks by developing an integrated view of diverse pressures and their interactions. This is an urgent necessity and requires such a large-scale project (Settele *et al*., 2007) because the final impact is caused by a combination of multiple stresses from different pressures. Given the multitude of pressures, the many driving forces behind them, and the diversity of impact mechanisms, it is a formidable challenge for any expert group or individual to encompass all aspects of biodiversity risk. Moreover, no single discipline and no single model (conceptual or numerical) can readily accommodate all of the relevant information. Rather, a broad, multi-disciplinary approach is suggested for assessing impacts on biodiversity, which will complement and integrate the achievements of smaller, targeted research efforts.

From the outset it was clear that multi-disciplinary collaboration was a necessary, though not sufficient, condition for meeting the project's objectives. What was needed was an integrated scientific approach, incorporating a mutual understanding of philosophies and methods and a genuine interdisciplinary mode of working. In this context, it transpired that scenario development can serve as a kind of 'melting pot', in which results from many individual research projects are synthesized into coherent pictures of possible future worlds.

Scenarios

How can scenarios be useful? Scenarios are not predictions but are a means to illustrate possible future developments under conditions of uncertainty, including different interpretations of the current situation (EEA, 2009). They deal with multi-variable state changes that are often too large in scale to be analysed empirically in a laboratory or greenhouse setting (Alcamo, 2001; Seppelt *et al*., 2009) or too inter-dependent to facilitate a meaningful analysis of changes in individual variables whilst fixing all others, i.e. the *ceteris paribus* assumption readily applied in economic theory (Scrieciu, 2007).

Uncertainty in this context cannot simply be described by a probability distribution or as a stochastic variation; rather it characterizes outcomes of human actions which are, by their nature, impossible to predict (van der Sluijs, 2002). Thus certain assumptions have to be made on how things might develop, and key criteria for a good scenario are that the assumptions are made explicit and cover all the relevant variables. This means that conclusions are derived from plausible reasoning and supported by model simulations for specific aspects of the scenario wherever possible, allowing comparative analysis of the scenarios, their dynamics and results regarding similar or differing trends across scenarios, bifurcation points, etc. The first part is the scenario narrative or story line, the second one the modelling (Alcamo, 2001).

Salience, credibility and legitimacy are three features that are of particular importance in the construction of effective and relevant scenarios (e.g. Dow & Carbone, 2007). For instance, a recent review of scenarios by the European Environment Agency (EEA) notes that 'even well-crafted scenarios can fail to have their intended policy impact if they present irrelevant information, lack support from relevant actors, are poorly embedded into relevant organisations or ignore key institutional context conditions' (EEA, 2009).

In order to be convincing, narratives must be internally consistent, take the existing institutional setting as their starting point and derive information relevant for the respective target group(s). Scenarios can be used for different purposes, e.g. in the decision-making processes or to convey a complicated scientific message to a lay audience (e.g. Nicholson-Cole, 2005; Jylhä *et al*., 2010). In our case, this means that they must be relevant to decisions with impacts on biodiversity and conservation taken by those making EU policy decisions.

Whether the scenarios meet these criteria is best evaluated by peer reviews within extended peer communities, involving not only scientists from different disciplines but also representatives of decision makers who are one of the key user groups of the scenarios. Extended peer communities are one characteristic of what has been called transdisciplinary research, and participation of key stakeholders as an integral component of research is part of what has been described as 'post-normal science', a method to be applied when facts are uncertain, values in dispute, stakes high and decisions urgent (Funtowicz & Ravetz, 1993, 1994). Only if a scenario (or a group of them) resonates with that audience can it be expected that it will be used in decision-making processes, and thus have an impact beyond the scientific community.

Scenario narratives can accommodate qualitative and quantitative data, and integrate otherwise incommensurable pieces of information (i.e. which cannot be aggregated into one index figure by mathematical means). Hence, they can provide a comprehensive view of possible – plausible but not necessarily probable – future developments, and can also address complexity. In this way, they serve as a means to explore the possible future outcomes of decisions taken (or not taken) now. Thus the storylines are the backbones of the scenarios. They are the qualitative part, defining philosophies, policies and instruments, which is complemented by a quantitative part, the scenario simulations (or modelling).

Modelling is not the core activity, but it provides an extremely helpful contribution to scenario building. Both qualitative and quantitative models can serve a useful role. Mental models are indispensable for constructing a plausible narrative, requiring that the assumptions behind arguments used to justify a storyline be laid open and thus made accessible to critical review. Numerical models are commonly required to represent physically or empirically based relationships between the critical driving factors of change and key outcomes. These can be used to simulate outcomes on the basis of pre-specified quantitative projections of future trends in key driving variables (chosen, for example, to be consistent with a given narrative storyline). Examples of key drivers include economic, demographic and institutional changes, for which official projections may exist over varied projection periods and geographical scales. By their nature, models are simplifications of reality, much less complex than the natural and social systems they emulate (Spangenberg, 2005), and there may be large uncertainties associated with their outputs. Thus the raw quantitative output from models is less important for interpreting a scenario result than the general tendencies revealed. These can then be integrated into the storyline and be related to data from other simulation runs, offering potentially fruitful insights even in cases where simulation results from a variety of (mental and technical) models appear to diverge.

SCENARIOS IN ALARM

Biodiversity is subject to a variety of different, and interacting, pressures. In its 2005 Environmental Outlook, the EEA identified the following major determinants of environmental change in Europe: the socio-economic context, demography, macroeconomy, technological developments, consumption patterns, energy and transport; agriculture, waste and material flows (EEA, 2005). In the pan-European environment report (EEA, 2007), they add geopolitics and international cooperation, globalization and trade, migration, and natural resources. The Millennium Ecosystem Assessment uses a slightly different terminology, identifying as direct drivers habitat change (land-use change and physical modification of rivers or withdrawal of water from rivers), overexploitation, invasive alien species, pollution and climate change. Indirect drivers behind many of the direct ones are then population change, change in economic activity, socio-political factors, cultural factors and technological change. Thus to assess future risks for biodiversity, different policy options related to all of these determinants have to be analysed. ALARM scenarios cover all of these issues as they are broad pictures of possible futures, focusing on biodiversity risks caused by a wide range of factors.

Biodiversity scenarios in general aim to analyse the driving forces and pressures causing the loss of biodiversity, quantified where possible using model simulations based on research data and case studies. Similarly, ALARM scenarios followed this procedure to estimate the effects of several 'pressure families' such as land use (see Box 1 on land use, below) or climate change (Hickler *et al.*, 2012) on species groups and ecosystems in different biomes (Marion *et al.*, 2010). By comparing the results, conclusions can then be drawn, highlighting which policy decisions would be more or less desirable from the point of view of biodiversity conservation. Consequently, each scenario has been designed to be archetypal for one such policy direction. Questions addressed include, for example, the impact of climate change on conservation (the EU Natura 2000 sites; Hickler *et al.*, 2012), the impacts of EU agricultural policies for trends in plant invasions (see Chytrý *et al.*, 2012) or the combined effects of climate change and land-use change on biotic interactions (see Schweiger *et al.*, 2008, 2012).

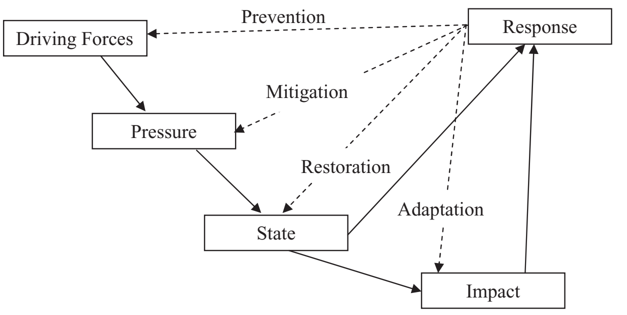

Figure 1 The DPSIR (distinguishing Drivers, Pressures, State, Impact and Responses) model. Solid lines: selected causal relations. Dotted lines: different types of responses.

Previous scenarios have followed a DPSIR approach (distinguishing Drivers, Pressures State, Impact and Responses; EEA, 2000), which was refined and popularized by the EEA due to its ability to integrate and systematize research results from a wide range of disciplines and its effectiveness as a means of communication to decision makers (Stanners, in press). The approach provides a structured description of the factors having an immediate impact on the state of the environment (the pressures), the driving forces behind them and the policy responses triggered. Drivers are the domain of social science analysis, responses are analysed in political science, impacts and state are the objects of natural science research, and the analysis of pressures is an interface of different disciplines, in ALARM as elsewhere. This more general concept was subsequently adapted to biodiversity (Maxim *et al.*, 2009, Fig. 1). In order to better understand the interaction of drivers and their cumulative impacts such as the interaction between persistent chemicals, climate and land-use change (see Paul *et al.*, 2012), we defined pressures as the interface of socio-economic and bio-geochemical components of social–ecological systems (Spangenberg, 2007a). The description of the anthroposphere as the domain of drivers was structured using a hierarchy of institutions from organizations/agents and mechanisms to orientations, derived from political science and adapted to sustainability policies. In this dynamic hierarchical system, all factors on all levels can influence each other (Spangenberg *et al.*, 2002). For instance, an orientation towards economic growth can trigger policies including reduced environmental standards (pollution), more transport (climate change, fragmentation) and more consumption (land use, overexploitation of resources). The orientation towards global markets and competitiveness that is behind current EU agricultural policies has led to intensification, including the intensive use of chemicals in monoculture-dominated landscapes. These factors have contributed significantly to biodiversity loss in the new EU member states and threaten to continue doing so (Kuldna *et al.*, 2009).

Box 1: explanation of land-use change in the scenarios

For the ALARM project, quantitative, spatially explicit and alternative scenarios of land use in Europe were developed for 27 countries (EU25 + Switzerland and Norway) at a 10′ grid cell resolution. Seven land-use types were modelled with an annual time step from a baseline year 2000 to 2080: urban land use, cropland, grassland, permanent crops, biofuels, forests and land in succession (abandoned agricultural land). The tool used for land-use modelling was MOLUSC, an automated European land-use change model. It uses interpretations of future trends in current European policy that have an impact on land use, notably the European Spatial Development Perspective (ESDP) and its role in planning policy, the effects of the Common Agricultural Policy (CAP) on agricultural production and rural development and nature protection policies through the NATURA 2000 site network. More details can be found in Reginster *et al.* (in press).

Changes in future land use were referenced to a baseline of the current land use as defined by the PELCOM database. PELCOM is a 1 km pan-European land-cover map derived from remotely sensed data. The classification methodology in PELCOM was based on a regional and integrated approach of the NOAA-AVHRR satellite data and ancillary information. PELCOM covers the whole of Europe and is freely available (http://www.geo-informatie.nl/projects/pelcom/ public/index.htm).

The ALARM land-use scenario results

The results of the land-use scenario development show different quantities and spatial patterns of land-use change for the three scenarios, although the basic trends of land-use change are the same for each of them (Fig. 2). Some of the largest changes involve the abandonment of agricultural land (cropland and grassland) with the greatest changes being observed for the scenario GRAS (GRowth Applied Strategy), then BAMBU (Business As Might Be Usual) and finally SEDG (Sustainable European Development Goal). Some of the abandoned agricultural land is used for biofuels and forestry, but in spite of these transitions, important areas of surplus land are assumed for all three scenarios, with again larger surplus areas occurring in GRAS than in BAMBU and SEDG. Almost 12 % of the European land area is assumed abandoned by 2050 in GRAS.

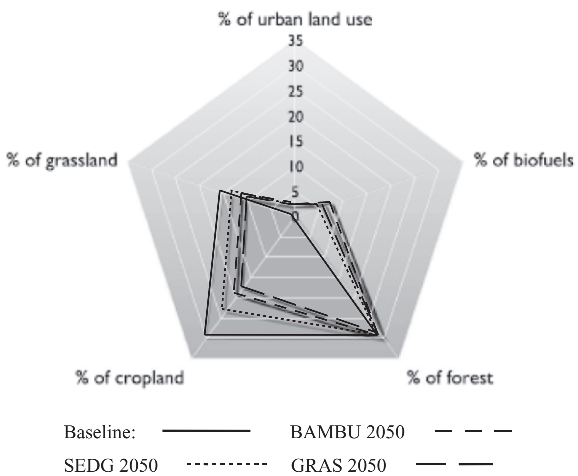

Figure 2 Synthesis of the land-use change in the ALARM (Assessing LArge-scale environmental Risks for biodiversity with tested Methods) scenarios.

Agriculture

European landscapes have experienced rapid changes in agricultural land use throughout the second half of the 20th century as a result of developments in technology and management driven by socio-economic and political forces. These trends are anticipated to continue into the future through the effect of reforms to the CAP, enlargement of the European Union, globalization, technological change and climate change (Rounsevell *et al.*, 2005).

For the three ALARM scenarios, different spatial patterns are observed for cropland and grassland, which reflect different allocation rules and the use of the agricultural rent map as a proxy for the optimal location of agricultural production in GRAS and BAMBU. For the GRAS scenario, the maps demonstrate large changes in land use with more regional disparities in these changes, especially in regions with lower agricultural rents such as the countries of eastern and southern Europe. For the BAMBU scenario, the maps demonstrate important land-use changes, with some regional disparities Agricultural land areas decrease in eastern and southern countries, but regulatory mechanisms maintain a certain level of rural activity in traditional rural regions even if these are not optimal compared with the intensive agricultural areas of western central Europe. For the SEDG scenario, the map shows slight changes in agricultural land use with fewer regional disparities.

The scenario outcomes suggest that the assumptions about the alternative future directions of the CAP would have significant effects on agricultural land use in Europe, liberalization of the CAP being associated with greater increases in abandonment of agricultural land. Irrespective of changes in the CAP, however, all three scenarios anticipate productivity increases resulting in some form of abandonment of agricultural land, which is consistent with the observed changes in European agriculture over the past 50 years. There are, however, important differences in the spatial patterns of this abandonment. This suggests that the directions of change are a robust outcome of the scenario analysis.

Forests

Even though the storylines describe rapid changes in societies, these changes may not be immediately reflected in forests but may take decades to materialize. It was assumed therefore

Box 1 *Continued*

that the underlying driving forces that are relevant to changes in forest land today would also apply in the future (Rounsevell *et al*., 2005). Generally, for the BAMBU and SEDG scenarios, managed forest areas increase. There could be some decreases in GRAS, partly due to competition with other land uses (urban land use or biofuels).

Urban areas

Urban land use increases in all scenarios, but these changes are small in areal terms relative to the other land-use classes. For the GRAS scenario, the map shows urban sprawl, peri-urban patterns and diffuse developments in rural areas. For the BAMBU and SEDG scenarios, the map shows more compact patterns. The local effect of urbanization is, however, especially important for ecosystems and in this respect very different patterns of urbanization are observed for the different scenarios. The dispersion of new urban settlements, such as in the GRAS scenario, will affect agricultural areas, forests and semi-natural areas, except in protected areas. For the BAMBU scenario, compact city development and limited peri-urbanization will reduce impacts on rural areas. Current protected areas are preserved and the NATURA 2000 site network is enforced. In the SEDG scenario, compact city development and limited peri-urbanization also minimize impacts on agricultural areas, forests and semi-natural areas.

Adapted from Reginster *et al*. (2010)

Based on such complex projections of policy impact, a list of geophysical and socio-economic changes was compiled describing these changes in a rough but structured way. Then an expert panel made up from the about 250 ALARM scientists assessed the impacts with regard to their relative strength and direction. Given the panel size, we consider this to be a reasonably reliable assessment, and it proved to be the most promising method of generating meaningful assessments and cross-comparisons of biodiversity impacts of the different scenarios (see also Marion *et al*., 2010).

Such scenarios can serve as the basis for developing and testing policy strategies to halt and reverse the loss of biodiversity in Europe (i.e. to implement the EU's core biodiversity policy objective; European Commission, 2010a). In the ALARM project, three policy scenarios were developed, representing three archetypal policy approaches (liberal, pragmatic and sustainable) and their corresponding implications for climate change, land use, chemical use, pollinator loss and their cumulative impact on biodiversity. The basic orientations were a joint choice of the ALARM scenario group (mainly consisting of the present authors); they were enriched by different disciplinary contributions, integrated and further developed in iterative discussions involving the scenario group, the socio-economic team, the Consultative Forum and the General Assembly of ALARM. To illustrate the scenarios by modelling, climate projections described in the IPCC Special Report on Emissions Scenarios (SRES; Nakićenović *et al*., 2000) that most closely corresponded to the scenario storylines were selected (see Fronzek *et al*., 2012). Key economic assumptions were transformed into parameters for the socio-economic model GINFORS (see Stocker *et al*., 2012); the new scenario generator MOLLUSC was developed for land use. Nitrogen flows and climate change were taken into account in the land-use model, which was also harmonized with GINFORS regarding the parameters playing a role in both models (see Fig. 3).

The ALARM scenarios provide decision makers and stakeholders with a picture of possible futures under the assumptions

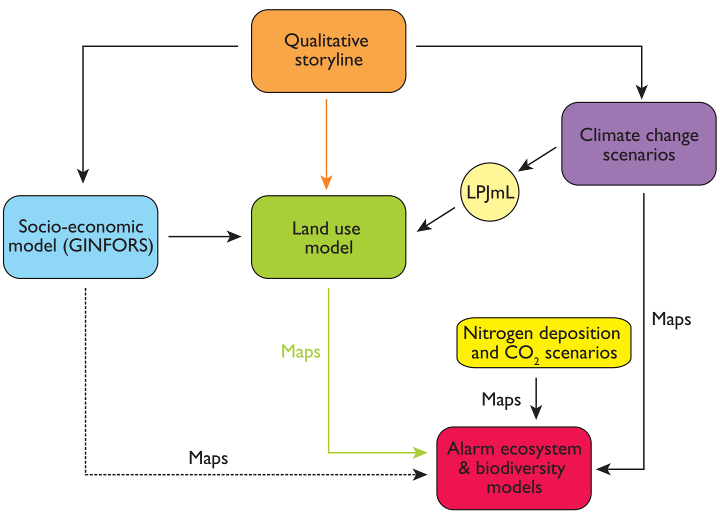

Figure 3 Information flows and elements (narratives and models) constituting the ALARM (Assessing LArge-scale environmental Risks for biodiversity with tested Methods) scenarios. All arrows symbolize information flows including maps; differences in shape and colour are to indicate the different sizes, scales and formats of the data/maps provided. GINFORS is the Global Interindustry Forecasting System; LPJmL is the Lund–Potsdam–Jena model for managed lands (Bondeau *et al*., 2007). Source: Spangenberg *et al*. (2010), by kind permission of Pensoft Publishers.

of the three distinct policy directions. Besides environmental trends and impacts on biodiversity, other relevant trends in policy domains from economic growth to social politics, demographic change, and foreign trade and policy relations are part of the scenario storylines. Thus the scenarios represent semi-quantitative multi-factor assessments for different policy options currently being discussed in the EU, based on the best available analyses and models. To allow the use of ALARM results in fact-based decision making, the project scenarios and policy recommendations were presented to a variety of decision makers in different Directorates General of the European Commission, the EEA, the European Parliament and to civil society decision makers in addition to the usual dissemination of information within the scientific community.

The ALARM scenarios

Simulations have been undertaken with several sectoral models (econometric, ecosystem, land use) and combined with outputs from other models (climate). As far as possible, the models have been coupled using the output of one model as input for another model and vice versa (Fig. 3). Using the combination of storylines (narratives) and modelling exercises we integrate climate scenarios (see Fronzek *et al.*, 2012) with potential yields from the ecosystem model LPJmL (Sitch *et al.*, 2003; Bondeau *et al.*, 2007) and a spatially explicit land-use model MOLUSC with the econometric input–output model GINFORS (see Stocker *et al.*, 2012). The latter calculates domestic economic development, combining economic data with energy flows, resource consumption, emissions and employment plus the global trade in some 40 categories of goods. Although LPJmL and GINFORS are global models, the focus of the analysis is one region, Europe, and how changes there affect the world (and vice versa).

Not all models have, nor need to have, the same spatial resolution, but in some cases interpolations based on the storylines were necessary. In particular, unlike climate and land use, economic development trends are not spatially explicit and cannot be disaggregated to a subnational level based on the available data as requested, e.g. by the MOLUSC model for assessing the impacts of land-use. Therefore rules were agreed on how to spatially differentiate population density, migration, income disparities and income development (based on Rounsevell *et al.*, 2005).

Core scenarios

In the ALARM project three core scenarios were developed (Spangenberg, 2007b). These scenarios are: a projection of status quo policies, a policy-driven liberal scenario and a normative backcasting (inverse projection) scenario of enhanced regional mitigation. The following three storylines form the framework of the ALARM scenarios. The acronyms derive from the diversity of graminoid species (for an overview of the assumptions made see Table 1):

1. 'Business As Might Be Usual' (BAMBU) is a policy projection scenario, i.e. a scenario extrapolating the expected currently known and foreseeable socio-economic and policy trajectories in EU decision making and assessing their sustainability and biodiversity impacts. Policy decisions already made in the EU are implemented and enforced, new ones follow the same development path. Thus BAMBU is not a business as usual (BAU) scenario, based on extrapolation of past trends, since recent or upcoming changes in EU policies would have been ignored in that case. At the national level as well, deregulation and privatization continue except in 'strategic areas'. Internationally, there is free trade. Environmental policy is perceived as another technological challenge tackled by innovation, market incentives and some legal regulation. The result is a rather mixed bag of market liberalism and socio-environmental sustainability policy.
2. 'GRowth Applied Strategy' (GRAS) is a coherently liberal, growth-focused policy-driven scenario. It describes a future world based on economic imperatives like primacy of the market, free trade and globalization. Deregulation (with certain limits) is a key means, and economic growth a key objective of politics actively pursued by governments. Environmental policy focuses on damage repair (supported by liability legislation) and some preventive action. The latter is designed based on cost–benefit calculations and thus limited in scale and scope.
3. 'Sustainable European Development Goal' (SEDG) is a backcasting (inverse projection) scenario, and as such is necessarily normative, focused on the achievement of a socially, environmentally and economically sustainable development. Based on the primacy of policy it is designed to meet specific goals and derive the necessary policy measures to achieve them, for example ending biodiversity loss. It aims at enhancing the sustainability of societal development by integrated social, environmental and economic policy. Policy priorities under SEDG include a competitive economy and a healthy environment, gender equity and international cooperation. SEDG represents a precautionary approach, taking measures under uncertainty to avoid not yet fully known future damages.

Shock scenarios

Scenarios are often undertaken as exercises to assess the consequences of current decisions using a rather linear, often monotonous, development trajectory without any sudden changes – this is what computer simulations most easily produce. Such simulations are not capable of illustrating the full range of potential (i.e. possible and plausible without necessarily being probable) futures. To better explore this broad spectrum, three 'shock scenarios' ('wild cards' or hazard-driven scenarios) were developed, considering one shock for each of the three dimensions of sustainability – environmental, economic and social.

These strong yet unexpected (i.e. considered very improbable at the time when the scenarios were designed at the beginning of the project in 2004) events have come close to reality in the mean time (Box 2). Whereas the probability allocated to the shocks has increased due to new insights, the probability of the shock scenarios cannot be quantified, as is the case for all sce-

Table 1 Summary of the ALARM scenarios: diverging policies in areas central for biodiversity pressure generation.

Scenario	GRAS	BAMBU	SEDG
Climate projection	Corresponds to the IPCC SRES A1FI storyline and its assumptions	SRES A2 (the best fitting SRES scenario available at the time of calculation, though SRES A1B would have fitted better to past emission trajectories)	SRES B1 (SRES scenario with the lowest emissions, but not as low as 450 p.p.m. CO_2 stabilization assumed so the SEDG storyline differs significantly from B1)
EU Common Agricultural Policy	Dismantling payments for production (1st pillar) and for rural development and environment (2nd pillar)	Shift from 1st to 2nd pillar results in polarisation: intensification of high yielding locations, neglect of low yielding ones	Spatially explicit support structure to maintain (organic) agriculture throughout the landscape (only the 2nd pillar transfers remain)
EU funds	Phasing out, considered as subsidies	Focused on infrastructure development and growth in poor regions	Focused on local green development and opportunities, education and employment
Energy policy	Efficiency, some renewable energies based on cost calculations	Efficiency, aiming at 20% reduction of greenhouse gas emissions by 2020, 80% by 2080. Increase in nuclear and renewable energy	Aiming at 75% reduction of CO_2 emissions by 2050 through savings, changing consumption patterns and renewable energies
Transport policy	Increased efficiency due to market pressure, no policy to shift the modal split or even reduce transport	Technological improvements and change in share of different modes of mobility (walking, cycling, trains, cars, boats, planes) – modal split	Transport reduction priority, plus modal split change (through pricing and infrastructure supply), technical improvements
EU chemicals policy: REACH	Focus on innovation and competitiveness. REACH not rigorously implemented	REACH implemented	REACH plus; filling gaps, e.g. for nano-materials, endocrine disruptors, metals.
Trade policy	Strong support for World Trade Organization and free trade	Promoting free trade except in 'strategic areas'	Global sourcing reduced for cost reasons; phytosanitarian controls

IPCC, Intergovernmental Panel on Climate Change; SRES, Special Report on Emissions Scenarios; REACH, registration, evaluation, authorization and restriction of chemical substances; SEDG, sustainable European development goal.

narios. Figure 4 shows the relations of base scenarios, unexpected transformative events (wild cards) and the resulting shock scenarios. The three shock scenarios are

1. Cooling Under Thermohaline collapse (GRAS-CUT) – the environmental shock. This describes collapse of the North Atlantic ocean water circulation (the most familiar part of it being the Gulf Stream, which warms the western coasts of Europe) and the resulting cooling of Europe. It is identical to the GRAS scenario until 2049, followed by a shutdown of the North Atlantic thermohaline circulation and consequent cooling. GRAS has been chosen as the base scenario for this particular shock as such an event is most plausible under a scenario representing a maximum impact of climate change.
2. Shock in the Energy price Level (BAMBU-SEL) describes the economic shock of a permanent quadrupling of the BAMBU

Box 2: 'shocks'

A shock is any event that comes unexpectedly and has the capability of changing the developmental trajectory of a system. Then a new direction of development emerges, starting at the shock point and distinguishing the shock scenario from its original, base scenario. Thus in the pre-shock period, a shock scenario is identical to the base scenario but then diverges from it along a new, hazard-induced trajectory.

The 'surprise factor' sounds simple, but is complex: the reasons for this usually consist of a mix of different factors like a lack of knowledge, the inherent uncertainty of future developments in complex systems, or plain human ignorance. In other words: ignoring emerging threats in decision making can reduce the resilience and enhance the vulnerability of a system, potentially turning what could have been a minor additional pressure into a substantive shock.

Because they assume deviations from a linear development trend, shocks are not as easily modelled as other scenarios, and commonly comprise simple storylines. Nonetheless, shock scenarios can support the development of surveillance systems for the identification of new threats and for dealing with them adequately from the very beginning of their emergence – they are special experiments exploring the impacts of artificially introduced hazards, simulating in a semi-quantitative narrative three singular events with widespread consequences.

Adapted from Streets & Glantz (2000) and Steinmüller & Steinmüller (2004)

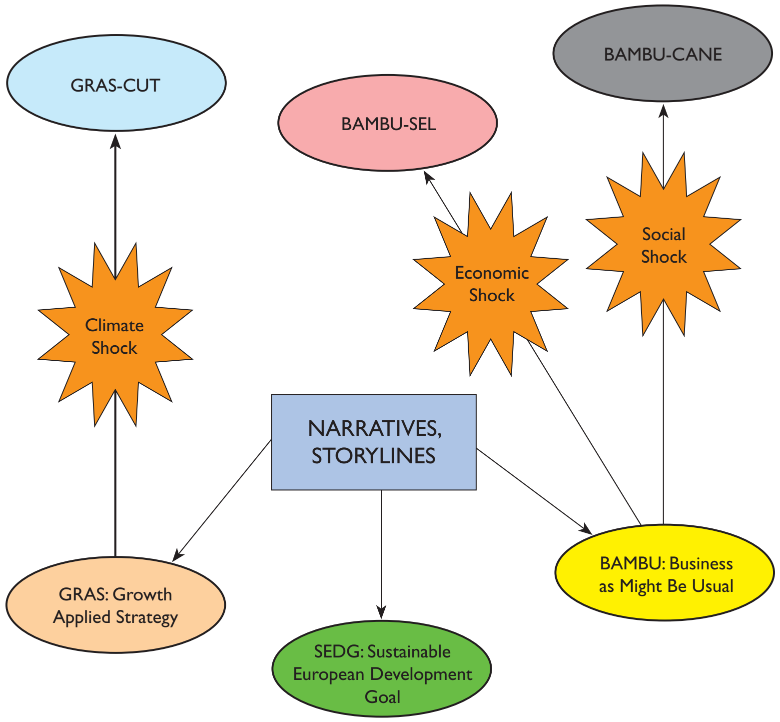

Figure 4 ALARM (Assessing LArge-scale environmental Risks for biodiversity with tested Methods) core and shock scenarios; shocks are conceptualized as deviations from core scenario trajectories following an unforeseen transformative event as described in the main text. GRAS-CUT, cooling under thermohaline collapse; BAMBU-SEL, shock in energy price level, BAMBU-CANE, contagious natural epidemic. Source: Spangenberg *et al.* (2010), by kind permission of Pensoft Publishers.

energy price, as expected when peak oil, the global maximum of oil production, has been passed (the USA had a taste of that in 2008 when the oil price rose from $20 to $120 per barrel, but not so in Europe, where the price only increased from about €35 to about €75 per barrel due to the increase in the euro exchange rate).

3. ContAgious Natural Epidemic (BAMBU-CANE) is the social shock, a pandemic out of control (WHO, 2005). Again, we had a taste of that, with Chinese bird flu in 2006 and the Mexican swine flu in 2009. Both BAMBU-SEL and BAMBU-CANE have been designed as deviations from the 'intermediate scenario' BAMBU, as no clear ex-ante information was available regarding which scenario would make either of the shocks more probable (unlike for GRAS-CUT). Similarly, no assessment of how the differences between the scenarios influence the impacts of shocks is available for the current state of research – otherwise it would have been tempting to run the same shocks on all three base scenarios.

LESSONS LEARNT

Climate change

Climate scenarios for ALARM consist of six projections from coupled atmosphere–ocean general circulation models (AOGCMs) operating at a global scale and a fairly coarse spatial resolution (typically 200–300 km) and one projection from a regional climate model (RCM), which downscaled AOGCM outputs to a finer (50 km) resolution over Europe. The scenarios embrace a number of key climate variables that are commonly used to study the impacts of climate on biodiversity. Averaged over Europe, the ALARM scenarios describe changes in mean annual temperature by the end of the 21st century relative to 1961–90 that range between 3.0 °C and 6.1 °C (Fronzek *et al.*, 2012). Changes in annual precipitation are between –1% and 6% with wetter conditions in northern Europe in winter and drier conditions in southern Europe in summer.

The ALARM climate scenarios are representative for the range of changes projected with a larger ensemble of climate model simulations employed by the IPCC in their Fourth Assessment Report (AR4; IPCC, 2007), while still being a manageable set of scenarios for studying the impacts of climate change on biodiversity.

The BAMBU scenario is represented by three simulations with AOGCMs and one RCM simulation. This offers a fair representation of model uncertainties for the same emissions scenario (SRES A2). The RCM projection also addresses uncertainties attributable to processes operating at sub-AOGCM scale. Since it is known that the spatial pattern of changes in temperature and (to a lesser extent) precipitation scales quite closely relate to different emissions scenarios (cf. Christensen *et al.*, 2007, p. 873), it was considered sufficient to represent the between-model uncertainties for only one of the emissions scenarios while portraying uncertainties in the climate response to different emissions by using results from the same AOGCM (also used in the BAMBU scenario) for all three scenarios. Finally, the GRAS-CUT scenario applied results from a special experiment to simulate the climatic effects of an abrupt shutdown of the North Atlantic thermohaline circulation (Vellinga & Wood, 2008) that was conducted with the same AOGCM supplying the climate scenario for the GRAS scenario. This scenario, imposed in 2050, produces sharp cooling and drying over north-west Europe relative both to the preceding (warming) conditions up to 2049 under the GRAS scenario and to conditions observed in the period 1961–90. The most extreme impacts include a drastic shortening in the thermal growing season of over 3 months in Scotland and Norway.

Socio-economics

Since the socio-economic scenarios only reflect changes that are expressed in economic parameters (in the case of GINFORS also energy and material flow inside the economic system, but not ecological processes), these trends and their impacts on biodiversity, ecosystems and their services cannot be reflected directly by the econometric model. For instance, changes in temperature and precipitation must be translated into agricultural losses or health costs, for example, before they can be taken into account. Shortages of resources are expressed as price increases, but absolute limits to their availability cannot be modelled (Scrieciu, 2007). Consequently, the user of such models should be aware of their limitations: societies and economies are complex evolving systems, with system elements (agents) able to reflect system trends and adjust their behaviour accordingly. The result is a system with changing structures and unpredictable behaviour in the medium to long term. Thus, econometric models which allow for structural change can only be meaningfully run over a limited time period of 20 years or less. In ALARM, the economic scenarios were modelled only until 2020, with some key variables projected (i.e. without taking further structural change into account) until 2050.

The economic research results (for more details see Stocker *et al*., 2012) confirm the limited *direct* economic impacts of climate change in the simulation period of the economic model for all scenarios.[1] Interpreting the model data, the storyline concludes that adaptation might happen rather easily in the business sector because the speed of change in the economic system is so much greater than in the geosphere, enabling entrepreneurs to relatively easily accommodate these changes in the environment into the investment planning of the business cycle. Even the indirect effects such as increasing risk of water deficits have no significant economic impact on the macro-scale of national economies the model represents. Thus it is not plausible to hope that price signals would lead to an automatic market reaction mitigating climate change, or that the business sector would act on its own behalf for cost reasons. Instead, dedicated political decisions are needed to set the right framework for climate change mitigation.

Furthermore, the simulation runs show that even a radical mitigation policy in Europe results in nothing more than a delay of a few years in global warming if other parts of the world do not follow suit. The conclusion for climate policy is that as the impacts – for example on biodiversity, but also on livelihoods in the Global South are serious, and thus action must be taken urgently and comprehensively – Europe is well advised to act as a frontrunner. International cooperation must then make sure that other parts of the world follow suit – maybe like-minded countries first, depending on policy processes that develop out of the apparent failure of the Copenhagen climate policy summit to agree on binding commitments supporting the politically agreed target of limiting the average global temperature increase to 2 °C (IISD, 2009).

Land use

The results of the land-use scenario development show different levels and spatial patterns of land-use change for the three scenarios and the shocks, although the basic land-use change trends are the same for each of them (for more details see Box 1 on land-use modelling).

Some of the largest changes involve the abandonment of agricultural land (cropland and grassland turning into surplus land, see Fig. 5), for which greater changes are observed for GRAS (due to imported substitutes) than for BAMBU and the lowest for SEDG (a result of assumed policies against large-scale land abandonment). Some of the abandoned agricultural land is used for agrofuels and forestry, without, however, going to extremes regarding the extension of agrofuel areas.

Regardless of these transitions, important areas of surplus land result from the assumed increases in agricultural productivity for all three scenarios, with again larger surplus areas occurring in GRAS (more imports) than BAMBU (leading to a polarization between highly fertile and less productive areas) and SEDG (assuming a transition to organic agriculture and no complete abandonment of any region).

According to the ALARM risk assessment, the impacts on biodiversity are mixed (see Hickler *et al*. 2012 and Schweiger *et al*., 2012). Taking the climate, economic and land-use drivers and their interaction into account, the scenarios demonstrate that under a 'markets first' scenario (GRAS), although environmental policy is not abandoned its impacts are limited and biodiversity continues to vanish in the EU. With BAMBU, including for instance the implementation of the EU REACH (regulation on the Registration, Evaluation and Authorization of CHemicals) system and ongoing reforms of the Common Agricultural Policy (CAP), the loss of biodiversity is slowed but not halted, let alone reversed. However, the likelihood of repeating past mistakes of environmental contamination with regards to environmental chemicals in general (Maxim & Spangenberg, 2009) and persistent organic pollutants (POPs) such as pesticides, flame retardants and insulators/refrigerants in particular is greatly reduced under REACH, while the impacts of climate and land-use change on the environmental fate and behaviour of historic POPs is likely to be negligible (Paul *et al*., 2012). In a sustainable development scenario like SEDG, with the combined effects of effective regulation and sustainable development goals, it is possible to halt or at least significantly slow the rate of biodiversity loss (Fig. 5 shows a

[1]Nordhaus (1990) finds the loss of 3 to 8 months of economic growth over a 50–100 year period. Stern (2006), on the other hand, expect economic damage worse than from a world war: economic scenarios depend heavily on the assumptions made.

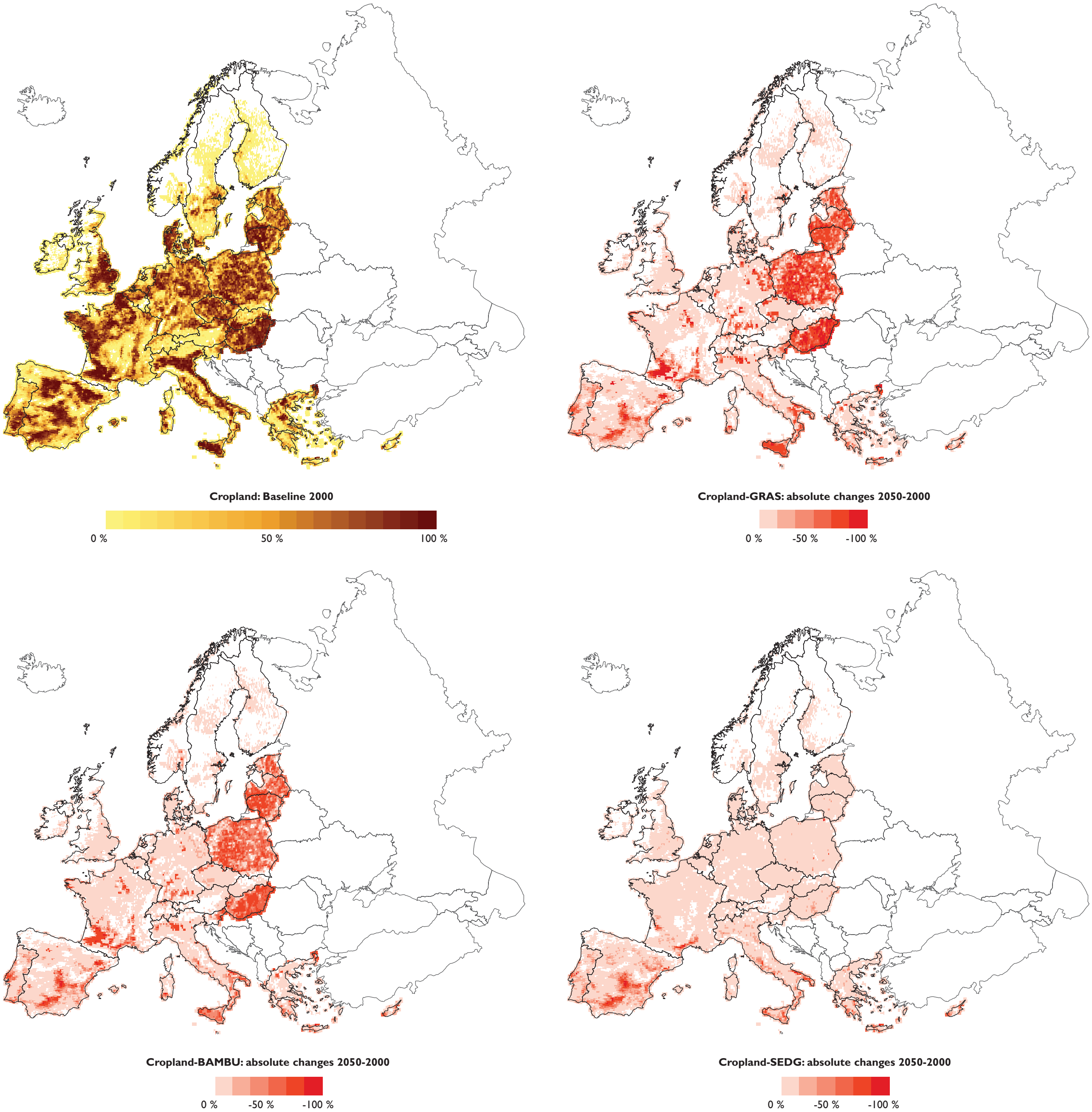

Figure 5 ALARM (Assessing LArge-scale environmental Risks for biodiversity with tested Methods) results: percentages of surplus land under different scenarios. Due to different economic dynamics and land-use policies, the increase in area of surplus land due to land abandonment develops differently between the scenarios. Source: Reginster *et al.* (2010), by kind permission of Pensoft Publishers.

comparison of the scenarios); in some cases a regeneration of biodiversity can even be expected.

One reason for these different results is that in both GRAS and BAMBU preservation of biodiversity is dealt with as an additional policy issue, and not rigorously implemented as a priority in all policy domains.

Shock(ing) lessons

The shock scenarios brought some surprising results: a collapse of the Gulf Stream, if occurring after 2050, has no major impact on Europe's economy, but is a stress factor for its ecosystems. Peak oil leads to a serious economic crisis when the oil price level suddenly and permanently peaks, but after a few years of more or less severe recession, the economy returns to its former growth path. Social cohesion is severely affected along with (assuming an additional focus on agrofuels) global and European biodiversity and the food security of the global poor. For a pandemic, depending on the assumptions regarding its spread and duration, the impact varies between minor economic losses and a total collapse of the economy and society.

The quadrupling of the oil price sounds like a safe recipe for an economic disaster, and so it could be (a simulation stretching the limits of the model resulted in a decline of a fifth in GDP, though for less than 5 years). However, with a competitive international market this depression does not last very long – economic growth bounces back to the old level (or even higher) as, due to international trade, the money that has flown out of the importing countries comes back in the form of product orders. As a result, as long as there is no absolute but only relative scarcity driving the prices up, the economic damage is significant but limited. However, since a high bill has to be paid for imports, the social impact is serious, resembling the wave of poverty resulting from the east Asian economic crisis of the 1990s. What would be the most plausible policy response? For Europe, a very large investment in biofuels was assumed. The result is a massive pressure on agricultural land, in Europe and even more so internationally, leading not only to significant losses of biodiversity but also to rising food prices (the food and the energy market are now interconnected) with major problems for the global poor. So what looks like an economic crisis turns out to be a social one, and the policies to mitigate it create an environmental disaster (even if they reduce greenhouse gas emissions) as well as a setback for global development. The impacts of mass hunger, resulting in food riots around the world in 2008 (United Nations, 2008), illustrate the kinds of events to be expected beyond what model simulations show.

A pandemic cannot be simulated, so the data we have are rough estimates based on modelling experience. The impacts of a pandemic depend on the assumptions regarding its spread and duration. However, their severity is not correlated with these factors in a linear fashion, but with a threshold phenomenon: at lower levels (up to a tenth of the labour force) of people dropping out of productivity an economic transformation occurs with some sectors losing and others winning, with an overall reduction of GDP below one-tenth and an early rebound. However, if about a fifth of the population or more drops out of the production process – some dead or on sick leave, but more of them trying to escape infection by avoiding situations where many people meet (as observed in the bird flu epidemic in China and swine flu in Mexico) the result is a total collapse of the economy. In this case, while reduced industrial activities would reduce some pressures on biodiversity, the population dispersal and settlement patterns assumed to emerge in the scenario that are neither planned nor controlled place a new heavy pressure on biodiversity.

Policy trends and scenario conclusions

Biodiversity protection needs to escape from the conservation policy niche to be effective (Council of the European Union, 2010); the scenarios illustrate the broad range of policies involved in effective biodiversity conservation. Thus the key challenge is to integrate biodiversity concerns into the day-to-day working mechanisms of state, business and society, beyond end-of-the-pipe solutions and compensations like establishing protected areas and ecological networks. Instead economic incentives and legal frameworks across societal sectors have to account for biodiversity as a fundamental aspect of sustainable development (Council of the European Union, 2010) and promote sustainable development as a condition for biodiversity conservation as the comparison of the scenarios demonstrates.

Developing effective strategies for biodiversity conservation is an international policy priority; the EU (the Commission and the Council, i.e. the heads of states and governments), after failing to succeed in halting the loss of biodiversity by 2010 as initially planned,[2] have now set as a new target to end biodiversity loss in the EU 'while reducing its negative impact on biodiversity beyond its borders'. By 2050, under the EU vision (Council of the European Union, 2010, p. 4; European Commission, 2010a), EU biodiversity and ecosystem services shall be protected, valued and appropriately restored. The mission headline target is 'halting the loss of biodiversity and the degradation of ecosystem services in the EU by 2020, and restoring them in so far as feasible, while stepping up the EU contribution to averting global biodiversity loss'. While on the one hand the Council (Council of the European Union, 2010, p. 5) stresses the need for this headline target to be 'fully reflected in the main cross-cutting EU policies and strategies, such as the Sustainable Development Strategy and the Strategy for Growth and Jobs (the future EU 2020 strategy)', the latter in particular demonstrates the complete failure of previous motions. 'EUROPE 2020', probably the key document for EU policies in the coming decade, includes no biodiversity targets but claims that policies on resource efficiency will deliver on biodiversity conservation (European Commission, 2010b). The objectives defined for transport, infrastructure, tourism and other policy areas, however, not only ignore biodiversity but threaten to increase the pressures leading to biodiversity loss. Except for a few green ideas, the new EU policy blueprint is somewhere between GRAS and BAMBU, but not at all leaning towards SEDG. This is unfortunate, as numerous ALARM studies and the results from a questionnaire addressing the ALARM experts (see Marion *et al.*, 2010, and Fig. 6) consistently show that:

1. GRAS provides the least desirable outcome for biodiversity in Europe – across different biomes, and for most ecosystems and species.
2. 'Muddling through' along the BAMBU path, although probably slowing down biodiversity losses, will systematically fail to meet the EU target to halt the loss of biodiversity by 2020 and beyond.

[2]The Council of the European Union (2010, p. 3) gives as reasons, amongst others, the 'incomplete implementation of legal instruments, incomplete and poor integration into sectoral policies, insufficient scientific knowledge and data gaps, insufficient funding' and is therefore 'convinced that the means have not matched the targets'. Sectoral policies needing to integrate biodiversity are (Council of the European Union, 2010, p. 6) 'agriculture, food security, forestry, fisheries, and energy, as well as spatial planning, transport, tourism, trade, and development.'

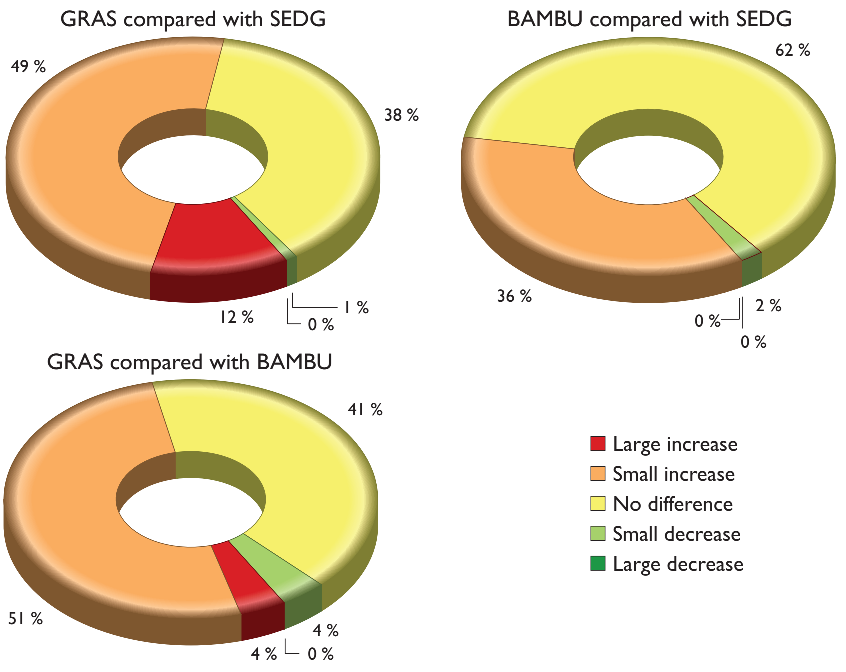

Figure 6 Risk of biodiversity loss in Europe, comparison of scenarios, aggregated over species groups. Results from a questionnaire addressing the scientists participating in ALARM (Assessing LArge-scale environmental Risks for biodiversity with tested Methods). Compared with BAMBU (business as might be usual) or SEDG (sustainable European development goal), GRAS (growth applied strategy) causes an increasing risk of biodiversity loss, while SEDG decreases the risk. Unaffected species include those not at risk today. From a biodiversity conservation point of view, a clear hierarchy emerges: SEDG > BAMBU > GRAS, although for a minority of cases (1–4%) the opposite is the case, with a small decrease in risk for the less sustainable scenario. Please note that large decreases do not occur; the category is 0% in all cases. Source: Spangenberg *et al.* (2010), by kind permission of Pensoft Publishers.

3. From a biodiversity point of view, SEDG represents a significant step in the right direction, although not sufficient in every respect (in some biomes some species and ecosystems are still lost).

For EU policies, this implies that although certain species and ecosystems may be stabilized under the EU policies modelled in the BAMBU scenario, the foreseen future policies are somewhere between GRAS and BAMBU and thus will not be able to deliver on the new 2020 targets. This general trend is unambiguous, despite significant differences between different species groups and between different ecosystems in different biomes. As most species and ecosystems benefit from a change in policy trajectory towards a more rigorous sustainability policy (SEDG), mainstreaming sustainable development in EU policies has to be considered a necessary condition for biodiversity conservation in the future. Simultaneously, current sustainability policies must be adjusted to better integrate biodiversity conservation.

ACKNOWLEDGEMENTS

The authors are indebted to the other members of the ALARM consortium, and in particular to the modelling and the socio-economic teams (Volker Hammen, Thomas Hickler, Laura Maxim, Iliana Monterroso, Martin O'Connor, Beatriz Rodriguez-Labajos, Marco Vighi) for contributions to the analysis presented here.

This paper is the result of work in the FP 6 Integrated Project 'ALARM' (Assessing LArge-scale environmental Risks for biodiversity with tested Methods), grant number GOCE-CT-2003-506675 (see http://www.alarmproject.net; Settele *et al.*, 2005).

REFERENCES

Alcamo, J. (2001) *Scenarios as tools for international environmental assessments*. EEA Expert Corner Report Prospects and Scenarios No. 5.Office for the Official Publications of the European Communities, Luxembourg.

Bondeau, A., Smith, P., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M. & Smith, B. (2007) Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology*, **13**, 679–706.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A. & Whetton, P. (2007) Regional climate projections. *Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller), pp. 847–940. Cambridge University Press, Cambridge, UK.

Chytrý, M., Wild, J., Pyšek, P., Jarošík, V., Dendoncker, N., Reginster, I., Pino, J., Maskell, L.C., Vilà, M., Kühn, I., Spangenberg, J.H. & Settele, J. (2012) Projecting trends in plant invasions in Europe under different scenarios of future land-use change: policy orientations will not reduce invasions. *Global Ecology and Biogeography*, **21**, 75–87 (this issue).

Council of the European Union (2010) *Biodiversity: post-2010. EU and global visions and targets and international ABS regime*. Council (Environment) Conclusions. Council Document 7536/10.Council of the European Union, Brussels.

Dow, K. & Carbone, G. (2007) Climate science and decision making. *Geography Compass*, **1/3**, 302–324.

EEA (2000) *Environmental signals 2000*. Environmental Assessment Report No 6. European Environment Agency, Office for Official Publications of the European Union, Luxembourg.

EEA (2005) *European environment outlook*. EEA Report 4/2005. European Environment Agency, Copenhagen.

EEA (2007) *The pan-European environment: glimpses into an uncertain future.* EEA Report 4/2007. European Environment Agency, Copenhagen.

EEA (2009) *Looking back on looking forward: a review of evaluative scenario literature*. EEA Technical Report No 3/2009. European Environment Agency, Copenhagen.

European Commission (2010a) *Options for an EU vision and target for biodiversity beyond 2010.* Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions COM(2010)4 fin. European Commission, Brussels.

European Commission (2010b) *EUROPE 2020. A European Strategy for smart, sustainable and inclusive growth*. Communication from the Commission COM(2010)2020. European Commission, Brussels.

Fronzek, S., Carter, T.R. & Jylhä, K. (2012) Representing two centuries of past and future climate for assessing risks to biodiversity in Europe. *Global Ecology and Biogeography*, **21**, 19–35 (this issue).

Funtowicz, S.O. & Ravetz, J.R. (1993) Science for the post-normal age. *Futures*, **25**, 739–755.

Funtowicz, S.O. & Ravetz, J.R. (1994) The worth of a songbird: ecological economics as a post-normal science. *Ecological Economics*, **10**, 197–207.

Hickler, T., Vohland, K., Feehan, J., Miller, P.A., Smith, B., Costa, L., Giesecke, T., Fronzek, S., Carter, T.R., Cramer, W., Kühn, I. & Sykes, M.T. (2012) Projecting the future distribution of European potential natural vegetation zones with a generalized, tree species-based dynamic vegetation model. *Global Ecology and Biogeography*, **21**, 50–63 (this issue).

IISD (2009) *Fifteenth conference of the Parties to the UN Framework Convention on Climate Change (UNFCCC) and Fifth Meeting of the Parties to the Kyoto Protocol (COP 15 and COP/MOP 5)*. ENB Summary Report. International Institute for Sustainable Development, Winnipeg, Canada. Available at: http://www.iisd.ca/climate/cop15/ (accessed 22 December 2009).

IPCC (2007) *Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller). Cambridge University Press, Cambridge, UK.

Jylhä, K., Tuomenvirta, H., Ruosteenoja, K., Niemi-Hugaerts, H., Keisu, K. & Karhu, J.A. (2010) Observed and projected future shifts of climatic zones in Europe, and their use to visualize climate change information. *Weather, Climate, and Society*, **2**, 148–167.

Kuldna, P., Peterson, K., Reginster, I. & Dendoncker, N. (2009) Agricultural land use and biodiversity changes in the new European Union member states. *Assessing biodiversity risks with socio-economic methods: the ALARM experience* (ed. by B. Rodriguez-Labajos, J.H. Spangenberg, L. Maxim, J. Martinez-Alier, R. Binimelis, N. Gallai, P. Kuldna, I. Monterroso, K. Peterson and M. Uustal), pp. 293–326. Pensoft Publishers, Sofia and Moscow.

Marion, G., Grabaum, R., Grescho, V., Butlaer, A., Bierman, S., Douget, J.-M., Hammen, V., Hickler, T., Hulme, P.E., Maxim, L., Omann, I., Peterson, K., Potss, S.G., Reginster, I., Settele, J., Spangenberg, J.H. & Kühn, I. (2010) Biodiversity risk assessment for Europe – putting it all together. *Atlas of biodiversity risk* (ed. by J. Settele, L. Penev, T. Georgiev, R. Grabaum, V. Grobelnki, V. Hammen, S. Klotz and I. Kühn), pp. 252–253. Pensoft Publishers, Sofia and Moscow.

Maxim, L. & Spangenberg, J.H. (2009) Driving forces of chemical risks for European biodiversity. *Ecological Economics*, **69**, 43–54.

Maxim, L., Spangenberg, J.H. & O'Connor, M. (2009) An analysis of risks for biodiversity under the DPSIR framework. *Ecological Economics*, **69**, 12–23.

Nakićenović, N., Alcamo, J. & Davis, G. *et al.* (eds) (2000) *Emissions scenarios. A special report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

Nicholson-Cole, S.A. (2005) Representing climate change futures: a critique on the use of images for visual communication. *Computers, Environment and Urban Systems*, **29**, 255–273.

Nordhaus, W.D. (1990) Greenhouse economics – count before you leap. *The Economist*, **316**(7662), 19–22.

Paul, A.G., Hammen, V.C., Hickler, T., Karlson, U.G., Jones, K.C. & Sweetman, A.J. (2012) Potential implications of future climate and land-cover changes for the fate and distribution of persistent organic pollutants in Europe. *Global Ecology and Biogeography*, **21**, 64–74 (this issue).

Reginster, I., Rounsevell, M., Butler, A. & Dedoncker, N. (2010) Land use change scenarios for Europe. *Atlas of biodiversity risk* (ed. by J. Settele, L. Penev, T. Georgiev, R. Grabaum, V. Grobelnik, V. Hammen, S. Klotz, M. Kotarac and I. Kühn), pp. 100–105. Pensoft Publishers, Sofia and Moscow.

Reginster, I., Rounsevell, M., Riguelle, F., Carter, T.R., Fronzek, S., Omann, I., Spangenberg, J.H., Stocker, A., Bondeau, A. & Hickler, T. (in press) The effect of alternative socio-economic and political strategies on European land use from 2006 to 2080. *Land Use Policy*.

Rounsevell, M., Reginster, I., Aráujo, M.B., Carter, T.R., Dedoncker, N., Ewert, F., House, J.I., Kankaanpäa, S., Leemans, R., Metzger, M.J., Schmit, C., Smith, P. & Tuck, G. (2005) A coherent set of future land use change scenarios for Europe. *Agriculture, Ecosystems and Environment*, **114**, 57–68.

Schweiger, O., Settele, J., Kudrna, O., Klotz, S. & Kühn, I. (2008) Climate change can cause spatial mismatch of trophically interacting species. *Ecology*, **89**, 3472–3479.

Schweiger, O., Heikkinen, R.K., Harpke, A., Hickler, T., Klotz, S., Kudrna, O., Kühn, I., Pövry, J. & Settele, J. (2012) Increasing range mismatching of interacting species under global change is related to their ecological characteristics. *Global Ecology and Biogeography*, **21**, 88–99 (this issue).

Scrieciu, S.S. (2007) The inherent dangers of using computable general equilibrium models as a single integrated modelling framework for sustainability impact assessment. *Ecological Economics*, **60**, 678–684.

Seppelt, R., Kühn, I., Klotz, S., Kabisch, S., Schloter, M., Auge, H., Görg, C., Frank, K. & Jax, K. (2009) Land use options – strategies and adaptation to global change. *GAIA – Ecological Perspectives for Science and Society*, **18**, 77–80.

Settele, J., Hammen, V., Hulme, P.E. *et al.* (2005) ALARM: assessing large scale environmental risks for biodiversity with tested methods. *GAIA – Ecological Perspectives for Science and Society*, **14**, 69–72.

Settele, J., Kühn, I., Klotz, S., Hammen, V. & Spangenberg, J. (2007) Is the EC afraid of its own visions? *Science*, **315**, 1220.

Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K. & Venevsky, S. (2003) Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic vegetation model. *Global Change Biology*, **9**, 161–185.

van der Sluijs, J. (ed.) (2002) *Management of uncertainty in science for sustainability*. Copernicus Institute, Utrecht University, Utrecht.

Spangenberg, J.H. (2005) Economic sustainability of the economy: concepts and indicators. *International Journal of Sustainable Development*, **8**, 47–64.

Spangenberg, J.H. (2007a) Biodiversity pressures and the driving forces behind. *Ecological Economics*, **61**, 146–158.

Spangenberg, J.H. (2007b) Integrated scenarios for assessing biodiversity risks. *Sustainable Development*, **15**, 343–356.

Spangenberg, J.H., Pfahl, S. & Deller, K. (2002) Towards indicators for institutional sustainability: lessons from an analysis of Agenda 21. *Ecological Indicators*, **2**, 61–77.

Spangenberg, J.H., Fronzek, S., Hammen, V., Hickler, T., Jäger, J., Jylhä, K., Maxim, L., Monterroso, I., O'Connor, M., Omann, I., Reginster, I., Rodriguez-Labajos, B., Rounsevell, M., Sykes, M.T., Vighi, M. & Settele, J. (2010) The ALARM scenarios. Storylines and simulations for analysing risks to biodiversity in Europe. *Atlas of biodiversity risk* (ed. by J. Settele, L. Penev, T. Georgiev, R. Grabaum, V. Grobelnki, V. Hamme, S. Klotz and I. Kühn), pp. 10–15. Pensoft Publishers, Sofia and Moscow.

Stanners, D. (in press) Indicators as a tool for policy learning: experiences moving from data to information. *Models and Indicators for Sustainable Development* (ed. by J.H. Spangenberg and N. Gosh), Springer, Berlin.

Steinmüller, A. & Steinmüller, K. (2004) *Wild cards*, 2nd edn. Murmann, Hamburg.

Stern, N. (ed.) (2006) *The Stern Review report: the economics of climate change*. HM Government, London.

Stocker, A., Omann, I. & Jäger, J. (2012) The socio-economic modelling of the ALARM scenarios with GINFORS: results and analysis for selected European countries. *Global Ecology and Biogeography*, **21**, 36–49 (this issue).

Streets, D.G. & Glantz, M.H. (2000) Exploring the concept of climate surprise. *Global Environmental Change*, **10**, 97–107.

United Nations (2008) *High level task force on the food security crisis – progress report April 2008–October 2008*. United Nations, New York.

Vellinga, M. & Wood, R. (2008) Impacts of thermohaline circulation shutdown in the twenty-first century. *Climatic Change*, **91**, 43–63.

WHO (2005) *Epidemic and pandemic alert and response (EPR)*. United Nations, New York.

BIOSKETCH

The ALARM scenario group was formed in the course of the ALARM project (for details see http://www.arlarmproject.net) to develop coherent scenarios and integrate the inputs from different disciplines. All participants have worked with models and scenarios in the past; the ALARM scenarios are their joint result.

J.H.S. led the storyline formulation and the integration of the components into coherent narratives, with input from all other team members, and particular support from J.S. and J.J. The climate scenario data were generated and provided by T.R.C., S.F. and K.J., A.B., I.R. and M.R. contributed the land-use model and harmonized it with the econometric model runs, which were designed by A.S., J.H.S. and I.O. The last crucial step, linking the overall developments to impacts on biodiversity, was contributed by M.T.S., A.P., O.S. and I.K.

Editor: Wolfgang Cramer