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Agriculture, Ecosystems and Environment 114 (2006) 57–68

Agriculture Ecosystems & Environment

www.elsevier.com/locate/agee

A coherent set of future land use change scenarios for Europe

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Abstract

This paper presents a range of future, spatially explicit, land use change scenarios for the EU15, Norway and Switzerland based on an interpretation of the global storylines of the Intergovernmental Panel on Climate Change (IPCC) that are presented in the special report on emissions scenarios (SRES). The methodology is based on a qualitative interpretation of the SRES storylines for the European region, an estimation of the aggregate totals of land use change using various land use change models and the allocation of these aggregate quantities in space using spatially explicit rules. The spatial patterns are further downscaled from a resolution of 10 min to 250 m using statistical downscaling procedures. The scenarios include the major land use/land cover classes urban, cropland, grassland and forest land as well as introducing new land use classes such as bioenergy crops.

The scenario changes are most striking for the agricultural land uses, with large area declines resulting from assumptions about future crop yield development with respect to changes in the demand for agricultural commodities. Abandoned agricultural land is a consequence of these assumptions. Increases in urban areas (arising from population and economic change) are similar for each scenario, but the spatial patterns are very different. This reflects alternative assumptions about urban development processes. Forest land areas increase in all scenarios, although such changes will occur slowly and largely reflect assumed policy objectives. The scenarios also consider changes in protected areas (for conservation or recreation goals) and how these might provide a break on future land use change. The approach to estimate new protected areas is based in part on the use of models of species distribution and richness. All scenarios assume some increases in the area of bioenergy crops with some scenarios assuming a major development of this new land use.

Several technical and conceptual difficulties in developing future land use change scenarios are discussed. These include the problems of the subjective nature of qualitative interpretations, the land use change models used in scenario development, the problem of validating future change scenarios, the quality of the observed baseline, and statistical downscaling techniques.

Keywords: Land use scenarios; Special report on emission scenarios (IPCC SRES); Climate change; Spatial allocation rules; PELCOM land cover data set; Land use modelling

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doi:10.1016/j.agee.2005.11.027

1. Introduction

The need to develop future land use change scenarios stems from the important role that human activities play in environmental quality. From ecosystem functioning and biodiversity to water resources and greenhouse gas emissions, land use is central to the landscapes around us. Therefore, an understanding of how land use might evolve is required in order to estimate how people will modify their environment in the future. In Europe, the most important land uses are agriculture and forestry, which cover about 45% and 36% of the total land area, respectively (FAO, 2003). Both land classes have changed considerably during the last decades. While agricultural land areas have declined by about 13% between 1961 and 2000 (Rounsevell et al., 2003), the area used for forest growth has increased steadily and has almost compensated for the contraction in agricultural land use (Kankaanpää and Carter, 2004a). However, the changes in both land use types are not directly related (Kankaanpää and Carter, 2004a) and involve a set of other factors that require consideration. A range of models has been developed to better understand, assess and project changes in land use and land cover (Veldkamp and Lambin, 2001; Parker et al., 2003; Veldkamp and Verburg, 2004). However, in spite of progress in integrating biophysical and socio-economic drivers of land use change (Veldkamp and Verburg, 2004), prediction of future land use remains difficult. Scenario analysis provides an alternative tool to assist in explorations of the future.

The work presented here reports the development of quantitative, spatially explicit and alternative scenarios of future land use in Europe (EU15, Norway and Switzerland), which were constructed to support analyses of the vulnerability of ecosystem services in the context of the EC funded ATEAM project (advanced terrestrial ecosystem analysis and modelling). The scenarios were developed for a range of different land use classes that reflect the principal uses of land in Europe. As many of the land use modelling and assessment methodologies for individual land use types have been published elsewhere (see for example Ewert et al., 2005; Rounsevell et al., 2005; Kankaanpää and Carter, 2004a,b; Reginster and Rounsevell, in press), the purpose of this paper is to synthesise both the methodological aspects of the scenario development (including the competition between different land use types) and the key results. The intention is not to repeat the detailed methodological descriptions given elsewhere, but to provide short methodological summaries and specifically to focus on a joint comparison of projected changes in the different land use classes. The paper attempts to highlight issues concerning the technical and conceptual limitations to land use scenario development, and discusses how land use scenario analysis might be developed further. This includes some initial effort to downscale the projected land use changes to finer resolutions more applicable for local impact studies.

2. Methods

2.1. Overview of the approach

The methodology was based on an interpretation of the four marker storylines (A1FI, A2, B1 and B2) of the Intergovernmental Panel on Climate Change (IPCC), special report on emission scenarios (SRES) (Nakićenović et al., 2000). Each SRES storyline describes different, socio-economic development pathways in terms of demographic, social, economic, technological and environmental drivers. The scenario logic is based on a matrix approach. Within this matrix, the vertical axis represents a distinction between more economically (A) and more environmentally and equity (B) orientated futures. The horizontal axis represents the range between more globally (1) and more regionally orientated developments (2). From this starting point, the scenario development method followed three basic steps:

1. *Qualitative descriptions* of the range and role of different land use change drivers were interpreted from the SRES storylines and for the European region;
2. *Quantitative assessments* were made of the total area requirement (quantity) of each land use type, as a function of changes in the relevant drivers for each scenario;
3. *Spatial allocation rules* (specific to each scenario) were used to locate the land use quantities in geographic space across Europe.

The approach was implemented using a range of techniques that were specific to each land use type (urban, cropland, grassland, bioenergy crops, forest land and protected areas), including reviews of the literature, expert judgement and modelling. These techniques are detailed below. The baseline year was fixed at 2000 and the scenarios were constructed for three time slices (2020, 2050 and 2080) for a 10-min (latitude/longitude) grid. The baseline (i.e. the current geographic distribution of land use) was used as the starting point for the construction of the scenarios and was derived from the PELCOM 1 km resolution land cover data set (Mücher et al., 2000) combined with the REGIO statistical database at the NUTS2 level (Eurostat, 2000).

2.2. Interpretation of the SRES storylines for Europe

The SRES framework has the advantage of coupling changes in the physical environment (climate change) with concurrent changes in socio-economic factors. This is because the different assumed socio-economic development pathways are responsible for different levels of greenhouse gas emissions and thus, climate change (Mitchell et al., 2004). However, the SRES framework is global in extent and so, its use for Europe first requires a translation of the global driving forces to the European scale. This was undertaken at two levels: an interpretation of cross cutting drivers that are relevant to the socio-economic background, and an identification of specific drivers that influence each land use type. These interpretations were based on an understanding of the land use drivers that are important for Europe using, where appropriate, knowledge of past and present European and national policy. For some land use types (e.g. forest land and protected areas), it was necessary to identify distinct regional trends in driving forces based on countries or country groups. In addition to the European scale qualitative descriptions, existing quantitative data sets for certain socio-economic indicators were also used, principally time series of population and gross domestic product (GDP) (Gaffin et al., 2004).

When dealing with land use change in Europe it is important to recognise that these changes will also be affected by events outside of Europe. This is especially important in relation to trends in global trade. Thus, land use in Europe reflects not only demand (and supply) of the internal market, but also the demand for land-based goods (e.g. food and wood products) that derive from elsewhere. Estimation of these demands requires the use of a model that simulates global trade patterns and in the work reported here, results from the IMAGE 2.2 integrated assessment model (IMAGE Team, 2001) were used for this purpose. IMAGE computes demands for agricultural and forest products (including animal products, food crops, grass and fodder species, wood and bioenergy crops) for OECD Europe and for each of the considered scenarios. These demands were used both directly in the quantitative assessments for agriculture, and as a crosscheck for the change in forest land areas.

2.3. Assessment of urban land use

The theoretical principles of *urban economy* were formulated into an urban land use model and this was used for the development of the urban land use scenarios (see Reginster and Rounsevell, in press). The model included a demand module and a spatial allocation module. The two main driving forces for urban demand were assumed to be: (a) population, reflecting demographic trends, and the demand for housing; (b) economic development, representing the degree of activity, types and intensity of activities, and economic dynamism. Urban demand estimates were calculated using an empirical–statistical model with population and GDP as the independent variables (Reginster and Rounsevell, in press). The future scenarios were based on the population and GDP data of Gaffin et al. (2004). A further four variables were used as pattern drivers, i.e. within the spatial allocation rules: (c) accessibility of the transport network, reflecting transport innovation and the quality of the infrastructure; (d) the severity of restrictions due to land use planning; (e) the relative attractiveness of small, medium and large cities (reflecting different urbanisation processes); (f) competition with other land uses (for example, urban development was not permitted in protected areas). Land use planning restrictions were imposed as a set of rules that restricted urban development at predefined distances from cities. The rules varied between scenarios (according to differences in the assumed levels of planning restrictions), and were based on expert judgement.

2.4. Assessment of agricultural land use including bioenergy crops

Ewert et al. (2005) and Rounsevell et al. (2005) give a detailed description of the development of the agricultural land use scenarios, but a brief summary follows. The drivers of agricultural land use change were identified as world supply and demand, market intervention (through agricultural policy), rural development policy, environmental policy, EU enlargement, resource competition (e.g. urbanisation and bioenergy crops), the role of the World Trade Organisation (WTO), and climate change through its effect on agricultural productivity. Scenarios of changes in agricultural areas for cropland, grassland and bioenergy crops were estimated for each of the scenarios using a combination of a simple supply–demand model at the European scale and scenario-specific spatial allocation rules. The basic premise was that agricultural land use areas would increase if the demand for agricultural goods also increased, but areas would decline if supply (productivity) increased, i.e. meeting the same demand (production) requires less land. Figures for the demand of agricultural goods were derived from the IMAGE2.2 model (IMAGE Team, 2001) and productivity changes were estimated as a function of climate change, CO_2 and technology (Ewert et al., 2005). The spatial allocation rules were implemented by taking account of policy and economic assumptions within the scenarios. Bioenergy crops were allocated after sufficient land had been allocated to food production using potential distributions determined for each bioenergy crop species (Tuck et al., 2006).

2.5. Assessment of forest land

It was assumed that the trends in forestry and forests of today would continue into the future until 2020. The changed circumstances described in the storylines were taken into consideration from 2020. Forests, however, have long rotation times in some regions, and trees planted today may only reach their harvesting age in 2080 or 2100. Even though the storylines describe rapid changes in societies, these changes may not be reflected in forests immediately, but may take decades to materialize. It was assumed, therefore, that the underlying driving forces that are relevant to changes in forest land today would also apply in the future. Many variables that describe forest land change are qualitative in nature and are difficult or impossible to describe in quantitative form. Moreover, forest policy is strongly national and sub-national in character (Kankaanpää and Carter, 2004a), in contrast to the dominance of EU policy for agriculture. For this reason, it seemed reasonable to assume that changes in forest land will be different in different regions of Europe and vary through time.

In the method reported here, percentage changes in forest land area, and the location of these forest lands were estimated from an interpretation of trends reported in the literature (which determined projections to 2020) and the IMAGE2.2 forest product demand figures (influencing longer-term scenarios). This was undertaken for country groups with similar characteristics in terms of forest policy and the role of forests: Group 1 (Norway, Sweden and Finland), Group 2 (Austria and Switzerland), Group 3 (Portugal, Spain, Italy and Greece), Group 4 (France, Germany, Luxembourg and UK), Group 5 (Belgium and Ireland), Group 6 (Denmark and Netherlands). Fig. 1 provides a summary of the estimated changes for the EU15, Norway and Switzerland. Further details are given in Kankaanpää and Carter (2004b). Adjustments to these change factors were also made to account for changes in other land use types. Forests that do not occur within designated (protection) areas were considered to be at the lowest level of the land use competition hierarchy and so, the change in forest land areas (given for example, in Fig. 1) were only considered up to the available land area within each grid cell.

For the A1FI and A2 scenarios, all increases in forest land allocation were taken-up by abandoned agricultural land. However, for two countries, Denmark and The Netherlands, it was not possible to allocate the increase in forest land area in this way in 2020 due to the absence of abandoned agricultural land. For the B1 scenario, all increases in forest land area were taken-up by abandoned grassland except for Denmark where the absence of abandoned agricultural land and the low percentage of grassland did not permit an increase in forest land. Forest land areas in Denmark remained, therefore, constant. For the B2 scenario, increases in forest land areas were allocated to cropland and grassland. Decreases in forest land areas were allocated uniformly within each country.

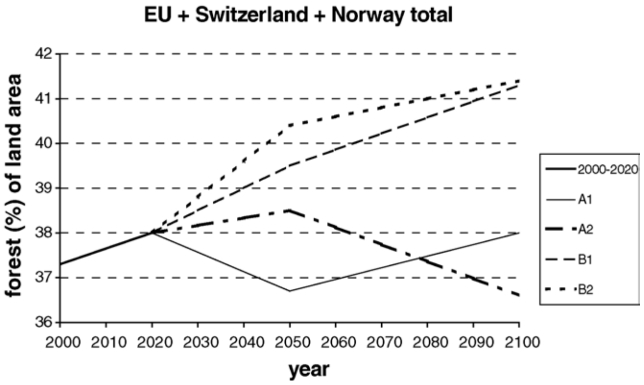

Fig. 1. Summary of the ATEAM forest scenarios from 2000 to 2100 for the European Union (excluding Luxembourg), Switzerland and Norway for the A1FI, A2, B1 and B2 scenarios.

2.6. Assessment of protected areas

The protected area methodology allowed an assessment to be made of the alternative (multi-functional) use of land for both conservation and recreational goals. Protected areas are a designation rather than a land use type because most protected areas enclose agricultural, forest and semi-natural landscapes. Thus, protected areas were evaluated after the principal land-based socio-economic activities were accounted for (as a post-processing exercise). The main drivers for protected areas were considered to be European and national policy for nature conservation, agriculture, forestry and spatial planning policy, as well as the demand for (green) recreation and tourism. Table 1

Table 1
Scenario assumptions for protected areas

	Nature conservation policy	Recreation and tourism
A1FI	More emphasis is put on the function of recreation within protected areas (access is possible). Less emphasis is put on the protection of biodiversity	Less emphasis on conservation and more emphasis on recreational land use and tourism. The recreational use of forests and protected areas increases
A2	Nature conservation policy is weak. There is little public concern for biodiversity. The current level of protection declines due to urban expansion. Networks of nature reserves are strongly fragmented	Tourism decreases (in the long term) and is mainly regionally oriented
B1	Strict protection of areas with high biodiversity. European ecological networks are established and maintained (European co-operation). Green belts around cities are preserved. Land not in agricultural production is developed for nature conservation. Forest areas with high biodiversity are designated as conservation areas	Demand for tourism (including eco-tourism) and recreation increases
B2	International conservation policies are difficult to implement. Much attention is given to the preservation of biodiversity and wildlife at the local level	Tourism and recreation decrease. The focus is on local destinations and distant recreation and tourism is not encouraged. There is demand for public access to conservation areas, and forest areas near to cities are used for recreation

outlines the qualitative scenario assumptions for protected areas.

An assumption was made that for all scenarios 20% of the area of Europe will become designated as protected by 2080. This assumption was based on a judgement made from past and current increases in protected-areas coverage in Europe, the latter being due to member-state responses to the need for implementation of the NATURA 2000 network. Whilst this target was the same for all scenarios, it was assumed that it would be reached for different reasons: the economic scenarios require areas for recreation for a richer population, whereas the environmental scenarios require areas designated for conservation purposes. The allocation (location) of these protected areas between scenarios was assumed, however, to vary substantially. For the regional scenarios (A2 and B2) the target was reached locally (i.e. representation goals were defined at a country-level) whereas for the global scenarios (A1 and B1) the target was reached European-wide. Furthermore, for the A1FI and A2 scenarios, economic priorities were assumed to lead to an opportunistic strategy for the location of new protected areas (Pressey et al., 1993). Their selection was based, therefore, on the minimisation of opportunity costs. Thus, less valuable land was designated for protection. For the B1 and B2 scenarios, environmental conservation priorities lead to a conservation strategy for the designation of new areas, and an assumption was made that new protected areas would maximise the conservation potential and biodiversity. Allocation rules were based, therefore, on the distribution of species and the need to increase the representation of species occurrences within reserves (e.g. Araújo et al., 2004).

Three criteria were used to identify appropriate locations for the A1FI and A2 scenarios:

1. Grid cells with less than 1% of urban land use: urban land use density was used as a ‘proxy’ for land cost.
2. Grid cells that were far from large cities (at a minimum distance of 50 km), from medium-sized cities (at a minimum distance of 30 km) and from small cities (at a minimum distance of 10 km). This also reflected lower land costs.
3. Grid cells that had more than 10% of land cover types with the lowest economic opportunities. For PELCOM, these were: forest, shrub land, wetlands, barren land, inland waters and permanent ice and snow.

Appropriate locations for the B1 and B2 scenarios were based on the ATEAM species distribution model for the Atlas Florae Europaeae (Araújo et al., 2005a), downscaled to the 10-min grid cells. New protected areas were identified as a set of scenario-locations that maximised species representation within reserves for a given increase in area.

The overarching assumption for the protected area calculations was that the land in these areas is managed in a way that is consistent with their stated (scenario-related) goals, i.e. for either conservation or recreation. Protected areas could account, therefore, for surplus agricultural land which could even continue to be managed as agricultural land (especially grassland ecosystems). They were assumed, however, not to contribute substantially to the European agricultural economy. Finally, it was assumed that the land use ’within’ protected areas remained unchanged compared to the baseline.

2.7. Competition between land uses

There is only a finite amount of the Earth’s surface available for land use activities, and the balance of different land uses within a geographic area reflects the competition between these different types. At any one location, one land use will have either a physical, economic or political advantage over other land uses and will, therefore, be more likely to be selected by a land user. Heterogeneous landscapes tend to develop where there is a large spatial variability in the physical, economic or political characteristics of a region, or where there is no clear advantage of one land use over another (land use decisions tend, in this case, to reflect a range of nearly optimal solutions, e.g. see Rounsevell et al., 2003). When constructing the land use change scenarios, therefore, account was taken of the competition for geographic space between the different land uses. This was based on a simple land use competition hierarchy:

$$\text{Protected (designated) areas} > \text{urban} > \text{cropland} > \text{grassland} > \text{bioenergy crops} > \text{commercial (unprotected) forest land} > \text{not actively managed}$$

The areal expansion of a ‘higher order’ land use type at a given location causes the contraction of a lower order land use at the same location. This results in the geographic displacement of the lower order land use at the expense of a land use even further down the order. Conversely, a contraction of a ‘higher order’ land use provides opportunities for the expansion of land uses at lower levels in the competition hierarchy.

Whilst urban land use takes precedence over other land uses, its geographic extent is limited by housing demand and by land use planning policies, which are a function of the scenarios. Bioenergy crops rank below other agricultural land uses because food production is assumed to take precedence over energy production. The hierarchy is also adjusted to account for productivity differences between some land uses. For example, in northern latitudes, forests would take precedence over agriculture because agricultural productivity is too low. The last level in the hierarchy is classified as ‘not actively managed’ (hereafter termed ‘surplus’). The surplus class represents land that remains after all economic land use activities have been accounted for, and in the main part represents agricultural land

Table 2
Summary of the European crosscutting drivers for each scenario

The A1FI scenario has very rapid economic growth and convergence between regions. European income inequalities are eradicated. Material consumption and increases in income/capital lead to the increased use of natural resources. European fertility rates reach 1.7 with a slight increase in population to 2050 then a decrease. There are high investments in technology and high rates of innovation. Governments are weak with a strong commitment to market based solutions and international co-operation flourishes. There is a stable political and social climate, with good health care and education. Self-sufficiency is not an issue and free trade is emphasised. There is a focus on centres and international connections, but rural development is not a focus area. Increased affluence has ‘‘spill-over’’ effects on rural and remote areas. Increase in recreation areas close to urban centres, and wilderness areas become less attractive. Increases in beach resorts and locations with built facilities rather than eco-tourism. Convergence of planning policy and fewer restrictions. EU enlargement proceeds rapidly

The A2 scenario has moderate GDP growth, but slower than A1FI. Economic development is regionally oriented and uneven. The income gap between developed and developing countries does not narrow. European fertility rates reach 2.1 resulting in a steady increase in the population. Technological development is slower than in A1FI and more heterogeneous. Technology transfer and diffusion are slower. There is self-reliance of regions with less mobility of people, ideas and capital. Social and political institutions diversify. Central national governments are weak because of the ‘‘markets first’’ approach. A more protectionist Europe compared to the present, which could mean a stronger European Union. Enhanced rural development is a by-product of the stress on regional self-reliance. Tourism decreases, but recreation increases with population increases. Demand for near urban recreation areas increases, but a dispersed population also uses distant areas for recreation. Built facilities are valued and wilderness areas are less popular. Heterogeneity of planning policy. EU enlargement stops or proceeds very slowly

The B1 scenario reflects a convergent world with global solutions to economic, social and environmental sustainability. There is progress toward international and national income equality. GDP growth rates are moderate. European fertility rates reach 1.7 with a slight increase in population by 2050 then a decrease. Rapid technological change. Central governments are strong with a high level of regulation. International institutions and cooperation is central. Rural development is a key issue with equitable income distribution and development a priority. Tourism decreases, but recreation increases, both near to urban centres and in remote areas. Spatial planning is homogeneous and restrictive with high levels of regulation. EU enlargement proceeds at a moderate rate

The B2 scenario has local solutions to economic, social and environmental sustainability. The rate of development and GDP growth rate are generally low. International income differences decrease at a slower rate than in A1FI and B1. Education and welfare programmes are pursued. Population is stable. Technological change and innovation are unevenly distributed. There is local self-reliance and strong communities. Decision-making is at the local/regional level and central government is weak. Citizen participation in decision-making is high and government policies and business strategies are influenced by public participation. Rural development increases because of emphasis on self-reliance and local products. Tourism decreases. Recreation increases nearer to urban areas and rural villages with access by public transportation. Spatial planning policy is restrictive and heterogeneous. EU enlargement stops

abandonment. A potential limitation of this hierarchical approach is that it does not account for changes in the land market.

2.8. Statistical downscaling

The results obtained at the 10-min resolution were further downscaled to a resolution of 250 m using statistical techniques. This was done for visualisation purposes, but also because subsequent use of the scenarios often requires data at a finer spatial resolution than 10-min. The approach (described in detail by Dendoncker et al., 2005) was based on the development of statistical–empirical models of land use suitability using historic, observed land cover datasets (the CORINE land cover map; European Commission, 1993). The land use change suitability surfaces were used in conjunction with the 10-min changes in land use quantities and the same hierarchical approach discussed above to derive 250 m resolution land use change scenarios. The approach used a purely spatial multinomial logistic regression model and an iterative procedure based on Bayes' Theorem. This allowed the suitability model to be derived solely from neighbourhood variables (i.e. an autoregressive model), which has the advantage of not requiring time-series of land use change maps, or a wide range of independent variables to explain land use patterns.

3. Results and discussion

3.1. Trends arising from the scenario assumptions

A summary of the interpretation of the cross cutting European drivers is given in Table 2. This qualitative information provides a rich contextual background that assists in understanding the scenario assumptions, and provides a means of cross checking the internal consistency within each scenario. The general, quantitative trends are summarised in Fig. 2 for the four SRES scenarios in 2080 using climate change scenarios from HadCM3: the general circulation model (GCM) of the UK Hadley Centre (see Mitchell et al., 2004). These trends show small increases in urban areas, large reductions in agricultural areas for food production (except for B1 and B2) partly compensated for by increases in bioenergy production, forest land and areas protected for conservation and/or recreation with surplus land in the A1FI and A2 scenarios. A complete set of maps for each scenario and for each land use type is available on CD or from the ATEAM project website (http://www.pik-potsdam.de/ateam).[1] A comparison of the direction of land

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[1] The ATEAM mapping tool (Metzger et al., 2004) provides a wide range of European-wide data sets of the results of the project, including the complete set of land use change scenarios. The CD is freely available or may be downloaded from the project website (http://www.pik-potsdam.de/ateam).

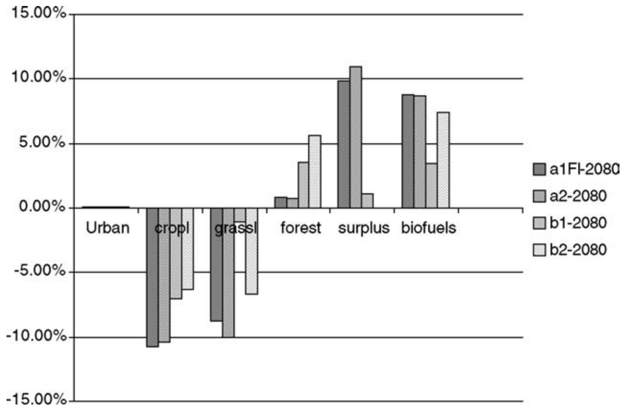

Fig. 2. Aggregated land use change trends in 2080 for Europe for the A1FI, A2, B1 and B2 (HadCM3) scenarios (the *y*-axis represents the absolute area as a percentage of the total European land area).

use change for the different scenarios and land use types shows that agricultural land uses decrease in all scenarios, whereas urban and forest land always increase. The changes are generally the greatest in the A1FI scenario and the least in the B1 scenario. Amongst the different land use types, agricultural land uses consistently change by the largest amount across all scenarios. The result of the large reduction in cropland and grassland areas is that little competition exists between land use types and so, large areas of surplus land occur that are not taken up by other land use types (see Fig. 3). The changes in urban areas are relatively small. These changes are, however, important at the local scale around existing urban centres and the spatial patterns of urbanisation are very different between the scenarios.

The large declines (by more than half) in the surface areas of agricultural land use (especially grassland) for the A (economic) scenarios are caused primarily by the assumption on the role of technological development (see Ewert et al., 2005; Rounsevell et al., 2005). These area reductions are partly compensated for by increasing bioenergy crop production and forest land. The consequence of this is that large areas of surplus land emerge within the A1FI and A2 scenarios (Fig. 3). It is unclear what would happen to this land. Declines in agricultural areas are smaller for the B (environmental) scenarios. This assumes, however, that the pressures toward declining agricultural areas are counterbalanced by policy mechanisms that seek to limit crop productivity. This could include measures to promote (a) extensification and/or organic production (particularly consistent in the environmental scenarios) and (b) the substitution of food production by energy production and the planting of trees, or an acceptance of overproduction (as with the current CAP). Forests benefit from the declines in agricultural areas with areal increases occurring for most scenarios.

Fig. 4 demonstrates differences in the spatial patterns of urban land use between the scenarios for the Iberian Peninsula. The results show the different levels of urban dispersion resulting from the different scenario assumptions, and development that extends along the transport network. Thus, whilst the quantity of change in urban areas is similar between the scenarios, the spatial patterns are very different reflecting alternative urban development processes, e.g. periurbanisation versus counter urbanisation.

Fig. 5 also shows the importance of alternative spatial patterns with an example of the downscaled scenarios for the region around Aberdeen, Scotland. The aggregate trends shown in Fig. 2 tend to mask the potentially large consequences at the landscape scale of alternative spatial patterns. Thus, the magnitude of land use change may be similar at the European level, but very different when spatial patterns are compared at the local level. The patterns shown in Fig. 5 demonstrate how the statistical downscaling approach leads to greater changes at the interface between two different land use types reflecting the assumptions that are made in the statistical model about the role of neighbourhood variables (Dendoncker et al., 2005). There is evidence to suggest, however, that many land use changes do in practice occur at land use interfaces and so, the results shown in Fig. 5 seem plausible. For example, deforestation occurs at the margins rather than within the centres of forests, and reforestation often occurs as an extension of existing forest land. Agricultural expansion and contraction also generally occur at the geographic limits of existing agricultural areas, for example, where these reflect altitudinal limits. These types of land use changes may reflect, for example, the advantages of similar soils and topographies or simply common land ownership. Further analysis of past, observed changes in land use would assist in refining the downscaling methodologies used in scenario construction.

3.2. What can be learnt from the ATEAM land use scenarios?

The ATEAM land use scenarios were developed to explore possible futures that encompass a range of uncertainties in environmental change development pathways. Some outcomes, however, were found to be common across the range of scenarios considered. For example, there was a common trend for agricultural land use to either decline in area or to become less intensive. In Europe, it is indeed difficult to envisage a scenario with agricultural land use expansion. This would require a substantial increase in the demand for agricultural goods, as well as stagnation in technological development and the management of agricultural production. Urbanisation increased in all scenarios in spite of different levels of population and economic growth, although the spatial patterns were very different. Whilst these types of results do not constitute a ‘prediction’ of the future, the occurrence of similar outcomes that arise from different assumptions, suggests a degree of coherence in future development trends (that is probably independent of the land use model used), although the spatial patterns

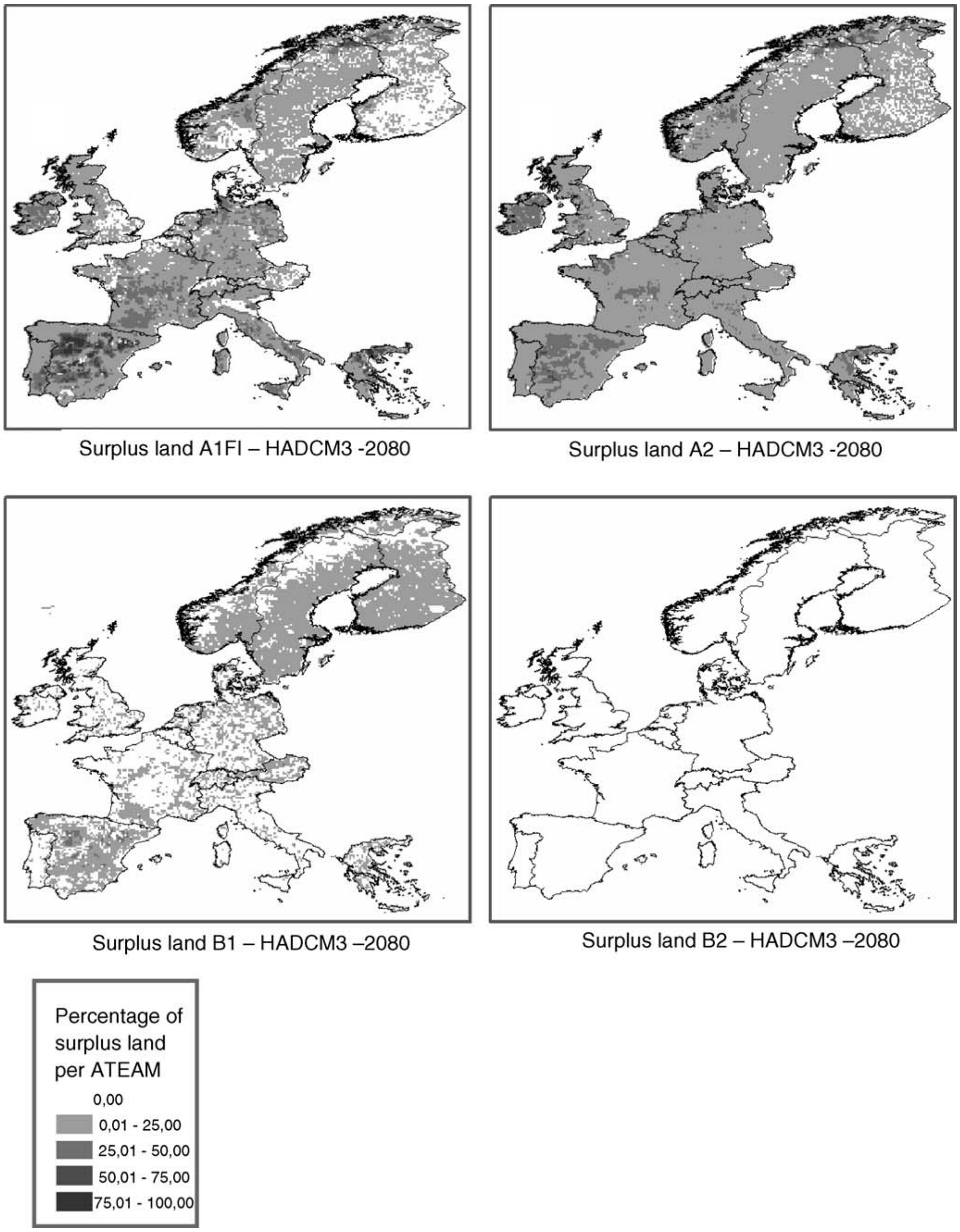

Fig. 3. Surplus land in 2080 for Europe for the A1FI, A2, B1 and B2 (HadCM3) scenarios, i.e. land abandoned from cropland and grassland including extensive grazing.

often remain quite different. Whether this could be translated into the ‘likelihood’ of certain futures occurring remains controversial, but exploring convergent or divergent behaviour in scenarios with different input assumptions may provide useful insights into land use change processes.

As ‘guided’ or constrained sensitivity analyses, scenario development provides further understanding of the potential role of different drivers and their relative importance for land use change. In the work reported here, this was evident with respect to the role of technology. Technological effects have rarely been analysed in other land use change studies, and the assumed magnitude of these effects remain contentious (see Ewert et al., 2005, for a discussion of this point). The work reported here, however, suggests that technology has an important role to play (especially for agriculture) and should be considered more explicitly in studies of both past and future land use change. How technology interacts with other drivers, such as climate change, is also of great importance.

3.3. Limitations and uncertainty in scenario development

The scenarios reported here, like all scenarios, have a number of limitations and uncertainties at both the technical

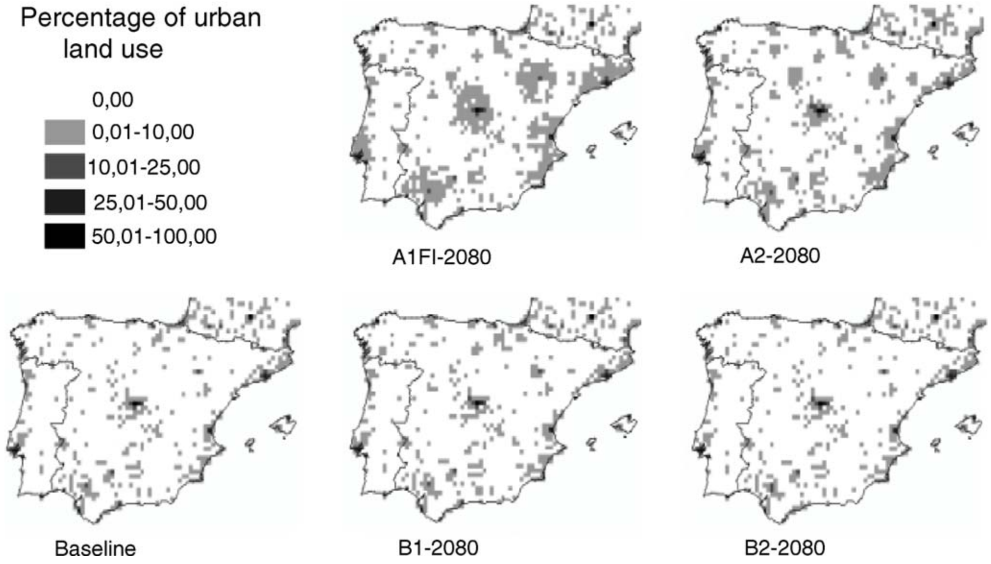

Fig. 4. The difference in urban development patterns around Madrid in 2080 for the A1FI, A2, B1 and B2 (HadCM3) scenarios.

and conceptual levels. Whilst scenarios provide a methodology for exploring the consequences of uncertainty, it is important that users of scenarios are aware of the additional uncertainties that can be introduced by the scenario methodology itself. These additional uncertainties include: (a) the subjective nature of qualitative interpretations, (b) assumptions underpinning the land use change models used in scenario development, (c) the problem of validating future change scenarios, (d) the quality of the observed baseline and (e) error within statistical downscaling techniques. Primary amongst these uncertainties are that scenario development involves interpretations based on judgements that may be subjective. In many cases different scenario developers would make a different judgement when faced with the same scenario framework. For example, within the SRES storylines, the notion of 'regional' could be interpreted at many different geographic levels from world regions, to nation states, to regions within countries, etc. Therefore, what is 'regional' becomes a judgement that must be made by the scenario developer and is likely to vary as a function of the geographic extent and objectives of a particular study. A further example of the subjective nature of storyline interpretations is the rate of technological development. Estimating future technological development is notoriously difficult, but is central to much thinking about future land use change (e.g. see Ewert et al., 2005). For example, the A1FI and A2 scenarios were here assumed to be more technologically innovative than the B1 and B2 scenarios because they are orientated toward economic growth. This is consistent with the SRES assumptions, but may not reflect reality. An alternative line of thought is to assume that economic protectionism would encourage innovation (because investment in technology is less risky in protected markets) with the result that the B2 scenario, in particular, would be more technologically advanced. Such an assumption would have profound effects on the results of the scenarios presented here.

The models on which many scenario exercises are built also contain uncertainties. It is important in this respect, however, to distinguish between the uncertainties in the values of model input parameters and the uncertainties of the model process formulations. When models are used to construct scenarios, their input parameters are changed in order to explore alternative futures and the inherent uncertainty of these parameter values is an acceptable part (or rather the *raison d'être*) of scenario analysis. Conversely, any lack in the capacity of models to represent land use change processes is a source of uncertainty in addition to that of the uncertainty of the future and should be minimised. This is not, however, a simple question of calibration/validation. Models validated on observed, past land use can be used to extrapolate into the future. However, since process understanding of land use change is still limited, land use models are often static, which limits their applicability for future predictions. Future changes of land use may not necessarily be described by relationships derived from historic observations. At present, it is impossible to reliably validate future land use scenarios as observations of the future do not exist and mechanistic understanding of land use change is insufficient (see also Araújo et al., 2005b). The past reflects only one realisation of a potential land use change pathway (Rounsevell et al., 2005).

Furthermore, many models that are used for scenario development only describe land use change processes that are endogenous to the region of study. Processes that influence a study region, but which occur elsewhere or at different scales are usually replaced by exogenous variables that must be derived from other models or sources of information. In the work presented here, for example, the

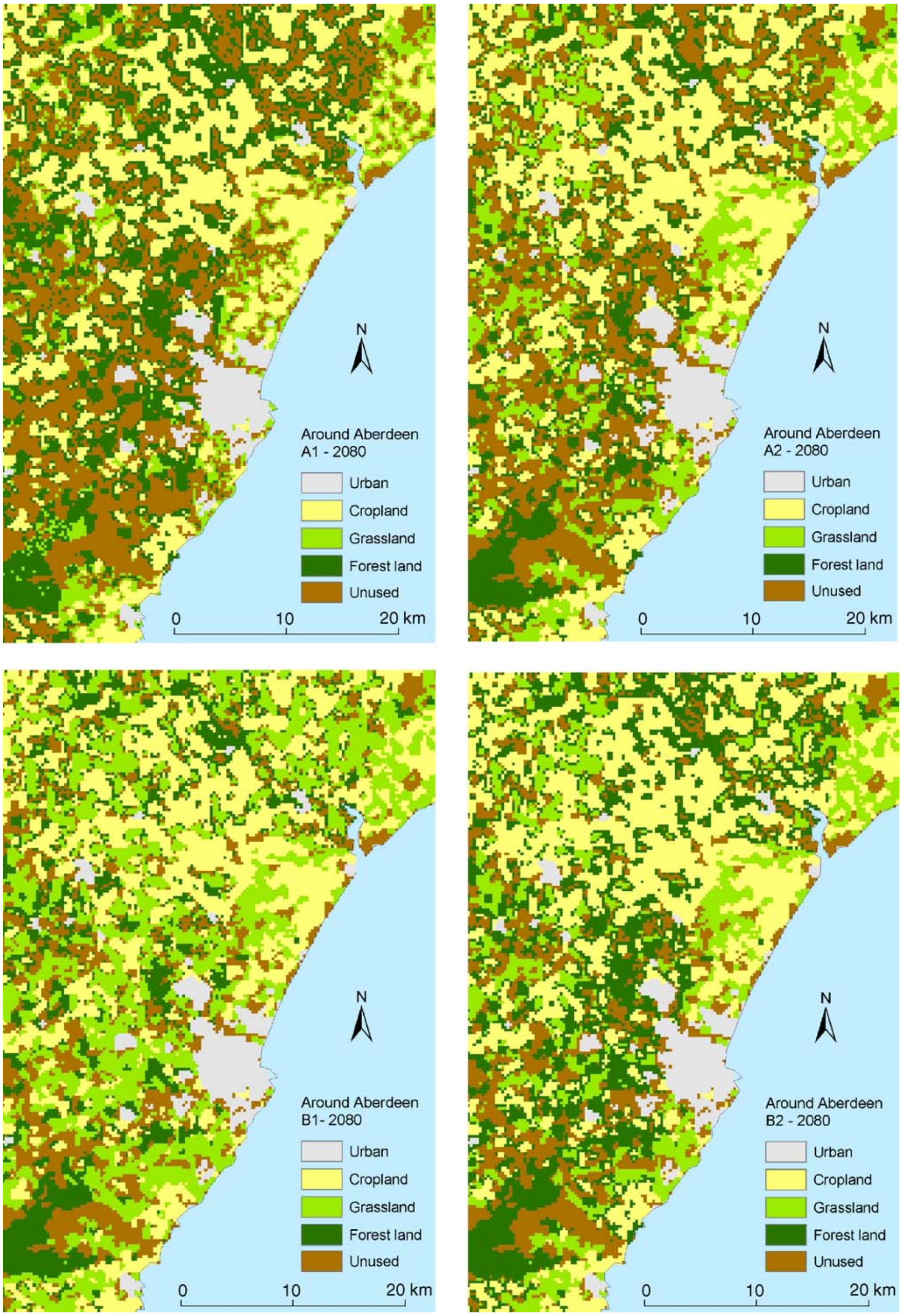

Fig. 5. Downscaled land use change patterns for the area of Aberdeen, Scotland in 2080 for the A1FI, A2, B1 and B2 (HadCM3) scenarios.

IMAGE model provided economic inputs that were a function of global trade processes such as the demand for different agricultural goods. This is a limitation of the scenario development methodology because the ATEAM land use models and IMAGE are only soft linked, i.e. there is a simple, unidirectional flow of data from one model to another, with no capacity for feedbacks within the whole system. Thus, the ATEAM land use change estimates do not influence the global trade quantities derived by IMAGE, which might be expected at the European scale.

Most land use scenario exercises commence with a defined baseline, i.e. an observed map of ‘current’ land use distributions and so any future projections are necessarily a function of the baseline conditions. For European land use scenarios, these maps are usually based on the CORINE or PELCOM land cover databases (as, for example, done here).

The accuracy of these maps tends to be accepted without question, although the data developers themselves recognise the data accuracy limitations arising primarily from the problem of representing heterogeneous landscapes at aggregated spatial resolutions (e.g. see European Commission DGXII, 2000; Schmit et al., 2006). Thus, the quality of the baseline data introduces a further source of uncertainty into the developed scenario, which is likely to impact on the results of subsequent analyses that use such scenarios. This uncertainty also extends to statistical, downscaling exercises (as undertaken here) that are based on observed, past land use distributions (see also Araújo et al., 2005b).

These uncertainties in scenario development are especially important as many land use scenarios are used in subsequent environmental change analyses. For example, the ATEAM scenarios have been used for the analysis of climate impacts on soil carbon stocks (Smith et al., 2005), ecosystem vulnerability (Metzger et al., in press; Schröter et al., 2005) and species distributions (e.g. Araújo et al., 2004, 2005b; Thuiller et al., 2004a,b). The propagation of errors and uncertainties from scenarios to subsequent modelling analyses is a problem that merits careful consideration.

Acknowledgements

The work presented here was undertaken within the framework of three European Union funded research projects: the ATEAM project (advanced terrestrial ecosystem analysis and modelling; EVK2-CT2000-00075), the ACCELERATES project (assessing climate change effects on land use and ecosystems: from Regional Analysis To the European Scale; EVK2-CT2000-00061) and the FRAGILE project (FRagility of Arctic Goose habitat: impacts of land use, conservation and elevated temperatures; EVK2-CT-2002-00145).

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