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Future scenarios of European agricultural land use II. Projecting changes in cropland and grassland

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Abstract

This paper presents the development of quantitative, spatially explicit and alternative scenarios of future agricultural land use in Europe (the 15 European Union member states, Norway and Switzerland). The scenarios were constructed to support analyses of the vulnerability of ecosystem services, but the approach also provides an exploration of how agricultural land use might respond to a range of future environmental change drivers, including climate and socio-economic change. The baseline year was 2000 and the scenarios were constructed for 3 years (2020, 2050 and 2080) at a spatial resolution of 10 min latitude and longitude. Time slices were defined for the climate scenarios as the 10 years before 2020, 2050 and 2080. The scenarios were based on an interpretation of the four storylines of the Special Report on Emission Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC) using a simple supply/demand model of agricultural area quantities at the European scale and the disaggregation of these quantities using scenario-specific, spatial allocation rules. The scenarios demonstrate the importance of assumptions about technological development for future agricultural land use in Europe. If technology continues to progress at current rates then the area of agricultural land would need to decline substantially. Such declines will not occur if there is a correspondingly large increase in the demand for agricultural goods, or if political decisions are taken either to reduce crop productivity through policies that encourage extensification or to accept widespread overproduction. For the set of parameters assumed here, cropland and grassland areas (for the production of food and fibre) decline by as much as 50% of current areas for some scenarios. Such declines in production areas would result in large parts of Europe becoming surplus to the requirement of food and fibre production. Although it is difficult to anticipate how this land would be used in the future, it seems that continued urban expansion, recreational areas (such as for horse riding) and forest land use would all be likely to take up at least some of the surplus. Furthermore, whilst the substitution of food production

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by energy production was considered in these scenarios, surplus land would provide further opportunities for the cultivation of bioenergy crops.
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1. Introduction

Because of uncertainties in social, political and economic development both within and outside of Europe, the future of European land use is unknown. Although it is not possible to predict future land use it is possible to explore what might happen given certain assumptions about societal developments and environmental change through the construction of scenarios. The scenario approach is widely used in many sciences (physical, economic, and social) in varied circumstances and for different purposes (Carter et al., 2001; Alcamo, 2001). Scenario thinking may offer solutions to complex issues for which there appears to be no simple analysis (Davis, 2002). Scenarios are coherent, credible stories about alternative futures. Importantly, scenarios are not projections, predictions or preferences of the future. Instead, the main idea of the scenario approach is to use multiple perspectives to explore a specific problem. Different definitions exist for the term 'scenario'. For the Intergovernmental Panel on Climate Change (IPCC) a scenario is defined as "*a coherent internally consistent and plausible description of a possible future state of the world*" (IPCC, 1994). The development and application of environmental change scenarios has been widely reported (e.g. Alcamo et al., 1996; Rotmans et al., 2000; Mearns et al., 2001; Nakićenović et al., 2000; Leemans, 1999; Carter et al., 2001). Previous attempts at the development of socio-economic change scenarios are less well developed and have tended to focus on qualitative descriptions (the Acacia project, Parry, 2000; the Visions project, Rotmans et al., 2000), short time-horizons and a 'best-guess' approach (the SeEOR project, Alexandratos, 1995), the global scale (Arnell et al., 2004) or have been constructed for small, well-characterised study regions (the RegIS project: Holman et al., in press-a, in press-b) or individual countries (Kaivo-oja et al., 2004).

There have been no published attempts to construct quantitative, spatially explicit and long-term land-use change scenarios across the whole European territory at fine spatial resolutions, i.e. resolutions that are relevant to ecosystem studies. One of the reasons for this is the difficulty in integrating the principal drivers of land use change (both biophysical and socio-economic) within an internally consistent framework (Carter et al., 2001; Lorenzoni et al., 2000; Rounsevell, 2000). The publication of the IPCC Special Report on Emissions Scenarios (SRES) (Nakićenović et al., 2000), however, has provided an appropriate starting point for the construction of such future land use scenarios. The SRES storylines are based on short narratives of possible developments during the 21st century, which are arranged around the level of globalisation (i.e. full globalisation versus closed regional blocks) and different values (i.e. emphasis on material values versus human and environmental values). The original SRES narratives described aggregated developments for four large regions. There is no particular order among the storylines. Each storyline represents a set of comparable but different not-implausible demographic, social, economic, technological and environmental developments. The two-digit code of the four families (A1, B1, A2 and B2) locates them in a four-quadrant chart. 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 (2) orientated developments. The A1 narrative was further developed into three groups, each with a specific set of energy sources (A1FI: fossil fuel intensive; A1B: a balanced mix; A1T: advanced technologies based on renewables). Because of the different socio-economic assumptions, each storyline has different levels of greenhouse gas emissions. All of the SRES narratives assume, however, that no specific climate polices are implemented and thus form a baseline against which narratives with specific mitigation and adaptation measures can be compared.

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A strength of using qualitative narratives, such as those developed by SRES, is that the assumed socio-economic changes not only relate directly to climate change through the emissions scenarios, but also to other aspects, such as impacts. Some impacts will be less or more likely in the different narratives. For example, a B1 world will use natural resources in a sustainable way and conserve biodiversity. This will certainly reduce the impacts of climate change. Thus, with such a narrative approach, it is now possible to develop scenarios that encompass the full range of socio-economic and environmental changes that could affect Europe in the future in an internally consistent way. A limitation of the SRES framework, however, is the geographical scale. SRES provides coarse scenarios derived for global scale applications, without guidelines to their application at the regional scale. Furthermore, the framework is generic and qualitative: it does not provide further descriptions of likely sectoral changes, such as for agriculture. Thus, in developing scenarios of future agricultural land use change within the SRES framework, it is still necessary to both interpret regional scale and sector-based change drivers as well as to quantify the effects of these change drivers. The narratives facilitate an interpretation that is internally consistent, although one that still remains subjective. Quantification of narrative storylines implies the need for appropriate 'tools' and models of land use change.

Whilst many types of land use change models exist (see Briassouli, 2000; Lambin et al., 2000 for comprehensive reviews) they are often too complex to apply at scales or resolutions that are appropriate for regional scenario studies (e.g. Rounsevell et al., 2003; IMAGE team, 2001; Verburg et al., 2002; Rabbinge and Van Oijen, 1997). Models used in the construction of land use change scenarios should be transparent with the modelled mechanisms including processes and parameter values that are well described and understandable. Otherwise the land use scenario becomes the product of a black box, and its underlying assumptions and hypotheses cannot be openly debated and criticised. The work presented here has attempted to develop, in a transparent way, a range of alternative, spatially explicit, quantitative scenarios of future agricultural land use in Europe. The paper includes a description of the development of a land use change modelling approach and its use in the interpretation of the SRES storylines. Presentation of the scenarios provides an opportunity for the discussion of both the limitations of such multidisciplinary approaches and of the future potential for agriculture in Europe. In doing so, the paper aims to raise awareness of some of the key issues facing the sustainability of European agroecosystems and the alternative ways in which agriculture might respond to environmental change drivers.

2. Methodology

2.1. Overview

The agricultural land use scenarios were developed for cropland (arable and permanent crops for food and fibre production) and grassland for the 15 European Union member states[1] (EU-15), Norway and Switzerland for the years 2020, 2050 and 2080. Time slices were defined for the climate scenarios as the 10 years before 2020, 2050 and 2080. The 10-year periods were preferred to the 30 year periods normally used to characterise climate because 10 years were considered to better represent the period over which land use decisions are made, i.e. farmers are more likely to make land use decisions based on recent experience of the weather rather than long-term (changing) climates. The 10-year periods were chosen as a compromise, therefore, between characterising the climate and characterising the socio-economic (decision making) context. The resolution of the spatial grid for this area was 10 min latitude and longitude (this is referred to subsequently as the ATEAM[2] grid). The land use baseline was derived from the PELCOM (Pan-European Land Cover Monitoring) land cover data set (Mücher et al., 2000), by aggregation from its original 1 km resolution to the 10 min ATEAM grid. The ATEAM grid was chosen as this represents the finest resolution at which trans-European climate and climate change scenario datasets are available. The grid provides, therefore, an appropriate scale at which

[1] The EU had 15 member countries at the time the present study was performed.

[2] This research was part of the EU-funded ATEAM project. ATEAM stands for Advanced Terrestrial Ecosystem Analysis and Modelling.

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to integrate climate and socio-economic drivers of future land use change.

The methodology was based on an interpretation of the four marker scenarios (A1FI, A2, B1, B2) developed within SRES (Nakićenović et al., 2000). The interpretation commences with a qualitative description of the potential drivers of change that might affect European agricultural land use in the future (Table 1). An assessment was then made of the total area requirement (quantity) of agricultural land use (ha) at the European scale, as a function of changes in the relevant drivers. This was achieved through the development and application of a simple supply/demand model for European agriculture that is presented below. The quantities of agricultural areas were then spatially distributed (disaggregated) across the European territory (to the ATEAM grid) using spatial allocation rules. The allocation rules were scenario-specific based on an interpretation of the SRES assumptions at the regional scale, specifying the location of land use change as a function of policy, political intent and/or land quality. The agricultural scenarios were also adjusted to account for increasing urbanisation with urban land use taking priority over agricultural production. Reginster and Rounsevell (2004) have also developed scenarios of European urbanisation based on SRES.

Consultation was undertaken with agricultural and forestry experts, as well as with stakeholders (i.e. individuals or organisations who have experience of working in related fields, in a decision-making capacity) in order to create a set of drivers and quantitative interpretations that were as plausible as possible. This was done through interviews with individuals as well as ad hoc stakeholder workshops organised as part of the ATEAM project (see de la Vega-Leinert et al., in press). The consultation process helped in both the identification of drivers and specification of the spatial allocation rules.

2.2. The drivers of agricultural change

Potential drivers of future agricultural land use change were discussed in relation to the Mediterranean region by Giupponi and Rosato (2003), and these provide a starting point for the European-wide work presented here. The drivers can be summarised as world supply and demand trends, market intervention (through agricultural policy), rural development policy, environmental policy, EU enlargement, resource competition (e.g. urbanisation, recreation, bioenergy crops), the role of the World Trade Organisation (WTO) and climate change through its effect on crop productivity (see Table 1). This list of drivers suggests that a model of future agricultural land use will need to take account of macro-economics through changes in trends of supply and demand, as well as policy changes that may act on the location of agricultural activities at a regional scale. Such considerations guided the development of the modelling approach presented below.

2.3. Supply/demand model

The future quantities of agricultural land use areas are calculated from a simple supply/demand model, which is fundamentally the same for both cropland and grassland (livestock) production. The basic idea is that agricultural land use areas will increase if the demand for agricultural goods also increases, but areas

Table 1
European agricultural land use drivers

Policy	Socio-economics	
	Demand	Supply
Market intervention (subsidies, quotas)	Population (consumption)	Resource competition (e.g. urban)
Rural development (LFAs[a])	Consumer preferences (meat, organic)	Climate change (temperature, precipitation, CO_2)
Environmental policy (NVZs[b], ESAs[c])	Market liberalisation (WTO[d])	Technology and management
	European Union enlargement	

[a] Less favoured areas.
[b] Nitrate vulnerable zones.
[c] Environmentally sensitive areas.
[d] World trade organisation.

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will decline if supply (productivity) increases, i.e. meeting the same demand (production) using less land.

The land use area for cropland or grassland (L, ha) at a future date in time (t) relative to the baseline (present-day) land use area (L_{t_0}) is derived from a calculation of the relative changes in supply and demand of agricultural goods between t_0 and t. It is assumed that at market equilibrium, supply (S) equals demand (D) and that the relative change in supply over time (S_t/S_{t_0}) is equal to the relative change in demand (D_t/D_{t_0}):

$$\frac{S_t}{S_{t_0}} = \frac{D_t}{D_{t_0}} \tag{1}$$

The relative change in the supply of agricultural goods is assumed to be the product of the relative change in productivity (P_t/P_{t_0}) and the relative change in land use area (L_t/L_{t_0}).

$$\frac{S_t}{S_{t_0}} = \frac{L_t}{L_{t_0}} \frac{P_t}{P_{t_0}} \frac{O_{r,t_0}}{O_{r,t}} \tag{2}$$

However, oversupply (O_r) is also accounted for and explicitly represents the fraction of supply that is above the required demand. If future oversupply does not change relative to the baseline, there is no effect on land use. Relative changes in supply are related inversely to relative changes in oversupply (see Eq. (2)). Thus, relative changes in land required for agricultural production are calculated from Eqs. (1) and (2):

$$\frac{L_t}{L_{t_0}} = \frac{D_t}{D_{t_0}} \frac{P_{t_0}}{P_t} \frac{O_{r,t}}{O_{r,t_0}} \tag{3}$$

The factors which are assumed to influence future productivity are the effects of temperature and precipitation changes (Cl), elevated atmospheric CO_2 concentrations (CO), and technology and management (T). Thus:

$$\frac{P_{t_0}}{P_t} = \frac{P_{t_0}}{P_{t_0} + ((P_{t,\mathrm{Cl}} - P_{t_0}) + (P_{t,\mathrm{CO}} - P_{t_0}) + (P_{t,T} - P_{t_0}))} \tag{4}$$

Setting the current productivity to one gives:

$$\frac{P_{t_0}}{P_t} = \frac{1}{1 + ((P_{t,\mathrm{Cl}}/P_{t_0} - 1) + (P_{t,\mathrm{CO}}/P_{t_0} - 1) + (P_{t,T}/P_{t_0} - 1))} \tag{5}$$

Thus, future land use is calculated as:

$$L_t = L_{t_0} \frac{D_t}{D_{t_0}} \frac{1}{1 + ((P_{t,\mathrm{Cl}}/P_{t_0} - 1) + (P_{t,\mathrm{CO}}/P_{t_0} - 1) + (P_{t,T}/P_{t_0} - 1))} \frac{O_{r,t}}{O_{r,t_0}} \tag{6}$$

As the demand for agricultural goods increases (between t_0 and t) the land area required for production of these goods also increases. It follows, therefore, that if the demand were to decrease, the land use areas would also necessarily decrease. Conversely, if productivity (the supply of goods per unit area) increases (between t_0 and t), the land use areas would decrease. In the same way, decreases in future productivity would lead to increases in land use areas. Application of the model requires an estimation of the individual model parameters.

2.4. Parameter estimation for each scenario

2.4.1. Demand for agricultural goods

One of the important issues when dealing with land use change in Europe is 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, wood products) that derive from outside of Europe. Estimation of these demands requires the use of an integrated assessment model that simulates global trade patterns. In the work reported here, the demand parameters were derived from the IMAGE 2.2 model (Integrated Model to Assess the Global Environment) for the OECD Europe region (Organisation for Economic Cooperation and Development) (Alcamo et al., 1998a,b; IMAGE team, 2001; Strengers, 2001). The IMAGE model is an integrated, dynamic model for simulating the global Earth system. IMAGE determines the environmental consequences of socio-economic changes (e.g. population growth and economic and technological development) for land use, energy use, emissions, climate, sea-level rise and ecosystems. The model runs at various geographical resolutions depending on the aspect being simulated, ranging from global (atmospheric CO_2 concentration), regional (17 individual world regions) and local (land and land use on a 50 km × 50 km grid). IMAGE is

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based on a vast amount of historical data and makes projections up to the year 2100 for each of the SRES narratives (IMAGE team, 2001).

The IMAGE-derived estimates of demand for animal products, food crops and grass and fodder species for OECD Europe were scaled to the EU15, Norway and Switzerland as a function of the geographic areas of the two regions (see Table 2). The A1FI scenario has the largest values for cropland because in addition to domestic European demand, exports are more important in an economic and globalised world. The B2 scenario has the smallest cropland demands as this is a non-economic and regionalised scenario for which exports are less important. A2 and B1 represent the situation between these two extremes. Table 2 also demonstrates that the demand values decrease for grassland for all of the scenarios. This reflects consumer preferences for the consumption of granivores (pigs and poultry) in place of red meats (cows and sheep) produced from grass-based systems. The declines are slightly less for the A1FI scenario reflecting the assumed higher consumption of red meats in a more affluent world.

2.4.2. Oversupply

The oversupply parameter values are given in Table 3. Oversupply was only considered for the economic (A) scenarios, and then only for cropland agriculture. For all other scenarios the parameter values were set to 1.0 (see Table 3), i.e. there is no over (or under) supply. An analysis of European Commission data suggested that the EU15 is currently oversupplying agricultural goods by about 10% (although this has been larger in the past). It is assumed, therefore, that total supply would need to diminish to 90% of current levels under a free market regime. For the B2 scenario, the assumption was made that no changes in agricultural areas would be permitted and that oversupply would be accepted, as in the current Common Agricultural Policy (CAP). As the land use areas do not change, it is possible to derive the value of the oversupply factor from the simple supply/demand model. This would provide information about either the amount of overproduction that must be accepted with this scenario, or the target for productivity declines that could be achieved through extensification. The same assumption is made for the B1 grassland areas.

Table 2
Relative changes in the demand for agricultural goods based on the IMAGE model (baseline = 1.00)

Scenario	Cropland			Grassland		
	2020	2050	2080	2020	2050	2080
A1FI[a]	1.25	1.51	1.46	0.85	0.87	0.85
A2[b]	1.14	1.31	1.38	0.91	0.67	0.64
B1[c]	1.18	1.39	1.29	0.91	0.67	0.64
B2[d]	1.06	1.09	1.07	0.91	0.67	0.64

[a] Global economic and fossil fuel intensive world.
[b] Regional economic world.
[c] Global environmental world.
[d] Regional environmental world.

Table 3
Assumed oversupply relative to the baseline (=1.00) for the different SRES scenarios

Scenario	Cropland			Grassland		
	2020	2050	2080	2020	2050	2080
A1FI[a]	0.90	0.90	0.90	1.00	1.00	1.00
A2[b]	0.90	0.90	0.90	1.00	1.00	1.00
B1[c]	1.00	1.00	1.00	1.00	1.00	1.00
B2[d]	1.00	1.00	1.00	1.00	1.00	1.00

[a] Global economic and fossil fuel intensive world.
[b] Regional economic world.
[c] Global environmental world.
[d] Regional environmental world.

2.4.3. Effects of changes in temperature and precipitation

For cropland, the effect of climate change (without CO_2) at the European scale was calculated from the change in yields between the baseline and each future climate scenario assessed for each ATEAM grid cell. The grid cell yield values are estimated with a simple empirical model that uses the EnC bioclimatic classification of Metzger et al. (2004). Each EnC class is allocated a yield value for the baseline using GIS techniques to intersect the geographical location of each EnC class with crop yield data at the level of NUTS2 (Nomenclature des Unités Territoriales Statistiques)[3] (Eurostat, 2000). For each new climate scenario, the

[3] Nomenclature of Territorial Units for Statistics. This is a hierarchical classification of European administrative regions used by Eurostat, the official statistical office of the European Union. There are more than 300 NUTS2 regions in the EU15, which vary in size between European countries, but which approximate to provinces.

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spatial location of EnC classes changes, and consequently new yield values are recomputed for each grid cell. For cropland, yield values for winter wheat were used as a 'proxy', as this crop is fairly ubiquitous in Europe and a good indicator of crop yield changes. The approach is described in more detail in Ewert et al. (2004), which also includes example crop yield maps.

For grassland, an intensity index was used as a proxy. This was derived from the baseline data for NUTS2 regions as the ratio of livestock numbers (computed as livestock units) to the area of grassland and fodder land use. The intensity index is, therefore, synonymous with, but not identical to, stocking density. As for the crop yield values, each EnC class was allocated a livestock unit per area value based on a spatial overlay of the EnC class and the Eurostat data at NUTS2 (Eurostat, 2000). Table 4 shows the estimated climate change parameters (aggregated for Europe) for both cropland and grassland. When aggregated to the European territory, regional differences tend to balance out, although there is a greater range of parameter values for grassland compared with cropland.

2.4.4. *Effects of increasing atmospheric CO_2 concentration*

Agricultural productivity increases due to elevated atmospheric CO_2 levels were estimated generically for each scenario. A maximum increase of +32% was calculated for the A1FI scenario in 2080 compared to 2000 for both cropland and grassland production (Ewert et al., 2004). This is a generalisation, but is estimated from current experimental and crop modelling literature. The SRES scenarios provide global CO_2 concentrations for each scenario, which are used to scale the difference in crop yield increase between the scenarios (providing internal consistency). The values used for the scenarios are given in Table 5 based on Ewert et al. (2004).

Table 5
Assumed effects of CO_2 for the different SRES scenarios (baseline = 1.00)

Scenario	2020	2050	2080
A1FI[a]	1.04	1.16	1.32
A2[b]	1.04	1.13	1.27
B1[c]	1.04	1.09	1.11
B2[d]	1.04	1.11	1.15

[a] Global economic and fossil fuel intensive world.
[b] Regional economic world.
[c] Global environmental world.
[d] Regional environmental world.

2.4.5. *Effects of technology development*

The effect of future technological change on crop yields is unknown, but assumptions about this are central to the evolution of agricultural areas. As crop yields have increased in some parts of Europe by as much as 300% in the past 50 years (Amthor, 1998), it is clear that assumptions about future yield increases are crucial. It is axiomatic that yields will increase because of technology in the future, but it is not known by how much. Opinions expressed in the literature differ on this point (e.g. see Amthor, 1998). Thus, an extensive literature review and analysis of historic yield trends was undertaken to establish the parameter values that are given in Table 6 (Ewert et al., 2004). Cropland was assumed to be more strongly affected by technological change than grassland systems because

Table 4
Estimated effects of climate (temperature and precipitation) change for the different SRES scenarios and HADCM3 GCM (baseline = 1.00)

Scenario	Cropland			Grassland		
	2020	2050	2080	2020	2050	2080
A1FI[a]	0.99	0.92	0.93	0.95	0.91	1.09
A2[b]	1.01	0.97	0.95	1.01	1.00	1.06
B1[c]	1.01	0.98	0.97	1.03	1.05	1.11
B2[d]	1.01	0.98	0.97	1.03	1.03	1.08

[a] Global economic and fossil fuel intensive world.
[b] Regional economic world.
[c] Global environmental world.
[d] Regional environmental world.

Table 6
Assumed effects of technology for the different SRES scenarios (baseline = 1.00)

Scenario	Cropland			Grassland		
	2020	2050	2080	2020	2050	2080
A1FI[a]	1.37	1.87	2.34	1.14	1.32	1.50
A2[b]	1.36	1.81	2.16	1.14	1.30	1.43
B1[c]	1.29	1.62	1.86	1.11	1.23	1.32
B2[d]	1.19	1.27	1.27	1.07	1.20	1.10

[a] Global economic and fossil fuel intensive world.
[b] Regional economic world.
[c] Global environmental world.
[d] Regional environmental world.

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a large part of grassland livestock production is extensively managed and thus, less able to benefit from technological advances.

2.5. Spatial allocation rules

Application of the European scale land use quantity model for the parameters given above leads, in all cases, to declines in agricultural areas. These area declines are allocated spatially using a set of rules that are specific to the previously defined characteristics and drivers of each SRES scenario. The rules for each scenario are presented below.

An exception to this approach was made for cropland and grassland located in designated areas, i.e. areas where land use is protected for conservation and recreation purposes. Data for designated areas were derived from the World Conservation Union (IUCN et al., 1998). For these areas, the land use was assumed not to change, as their protection status would prevent such changes.

2.5.1. Rules for the A1FI scenario

As a globally (non-regional) and economically orientated scenario, all agricultural production are assumed to be centred on optimal locations. This is intended to generate a pattern of land use change that is spatially uneven and which favours good production areas over poorer quality regions. The European Union introduced a policy measure within the rural development pillar of the CAP to subsidise agricultural production in Less Favoured Areas (LFAs). LFAs are, by definition, agricultural areas that are economically marginal and provide, therefore, a useful spatial indicator of non-optimal production areas (see Fig. 1). Optimal locations are assumed to be agricultural land that occurs outside of LFAs. Thus, allocation of the decline in land areas estimated at the European scale is assumed to be first taken up by the LFAs. Any remaining declines are then accounted by non-LFA areas.

LFAs only exist for the EU15. A simple approach was used, therefore, to estimate LFA areas and

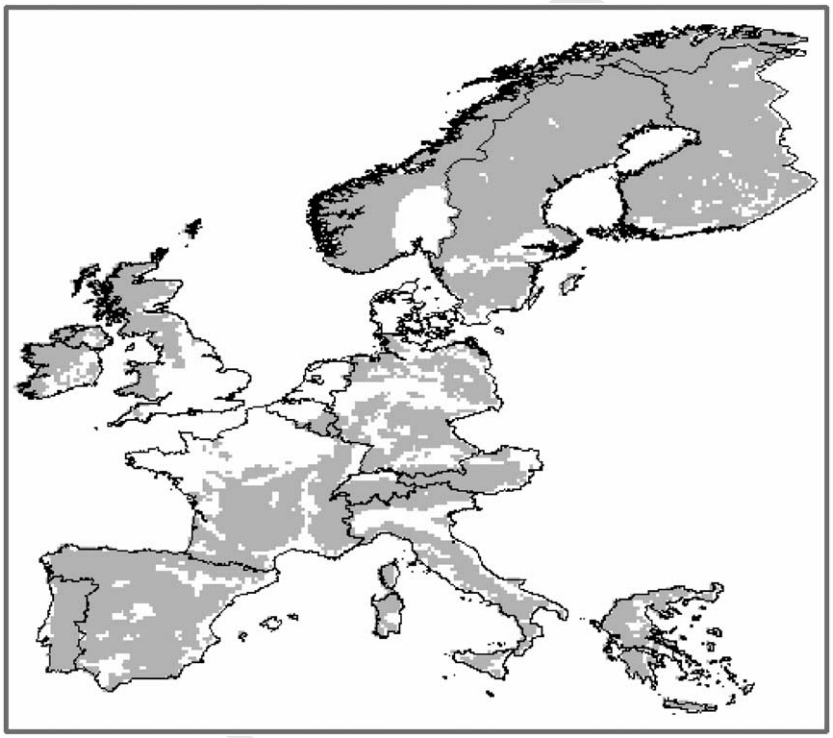

Fig. 1. Less favoured areas (LFAs) of the Europe union (indicated in grey) including estimated areas for Norway and Switzerland.

locations for Norway and Switzerland. The basic assumption being that in a global scenario, Norway and Switzerland would become more similar to the EU15 within a larger, but looser Union of European states and would, therefore, implement the LFA measures. The LFA area estimations were done by identifying the areas of Norway and Switzerland that had similar physical characteristics (e.g. elevation and land cover type) to the LFAs in neighbouring countries. In practice, the productive lowland areas of these mountainous countries were, therefore, considered to be more suitable for agricultural production and thus, were included within the optimal agricultural areas of Europe.

2.5.2. *Rules for the A2 scenario*

As a regionally orientated scenario, all land area changes were distributed equally between the European regions. This implies a certain degree of regional protectionism for reasons of national food security. Thus, the change factors estimated at the European-scale were applied equally to each ATEAM grid cell. As for A1FI, no declines in cropland and grassland areas were permitted in designated areas.

2.5.3. *Rules for the B1 scenario*

As an environmentally/equity-orientated scenario, oversupply was allowed where this both benefits the environment and maintains farmer incomes and rural communities. This means that no declines in grassland areas were permitted. As a globally orientated (non-regional) scenario, however, cropland production is centred on optimal locations (as for A1FI). This is also a strategy that may have potential beneficial effects in terms of reducing environmental impacts, and is consistent, therefore, with the B1 scenario assumptions.

2.5.4. *Rules for the B2 scenario*

As an environmentally/equity-orientated scenario, oversupply was allowed where this both benefits the environment and maintains farmer incomes and rural communities. This means that neither declines in cropland nor in grassland areas were permitted. It is assumed that as an environmental scenario this oversupply would be offset by policy measures which seek to reduce productivity by encouraging extensification and organic production.

2.5.5. *Production of bioenergy crops*

The scenarios described here also attempt to represent potential future changes within the agricultural sector resulting from the substitution of food production by bioenergy production. Whilst the model presented above deals explicitly with changes in food supply and demand, it does not deal with the equivalent processes for bioenergy production. There are many uncertainties concerning the estimation of plausible, future trends in bioenergy production, which makes the construction of scenarios of this land use difficult in practice (Leemans et al., 1996). It is assumed here, however, that the production of food from agriculture would always take precedence over the production of energy. Thus, a set of (post-processing) allocation rules were introduced to assess bioenergy crop areas based on the land that remains after accounting for food production. These areas are allocated to suitable production areas with surplus agricultural land within the overall areal quantities of bioenergy production estimated for the SRES storylines by the IMAGE model. For the B scenarios, bioenergy production is assumed to compensate partly for the overproduction resulting from the assumed constant agricultural land use areas.

2.6. *Statistical comparison of scenarios*

In order to quantify the relative differences (or similarities) between the scenarios, the results were compared statistically. A limited number of statistical tests were applied:

1. calculation of the number of ATEAM cells with the presence of each land use class, and the number of cells for which the spatial coverage of a class was 100%;
2. calculation of the Pearson correlation coefficients between each scenario (as a global measure of spatial patterns);
3. calculation of the mean land use areas per country (to identify regional change patterns).

3. Partial model validation

There is always a difficulty in validating future scenarios because alternative futures provide realisations that have not occurred in the past and for which,

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therefore, there are no observations. Thus, it is not possible to validate the spatial allocation rules presented in this study. Moreover, different interpretations of the spatial allocation rules are possible. For example, agriculture within the A2 scenario could alternatively be located at optimal locations within each country (region) rather than the area changes being distributed uniformly. This would give very different spatial patterns.

It is, however, possible to undertake a partial validation of the supply/demand model against land use change over the past 40 years by estimating the values of the parameters given in Eq. (6). This is only a partial validation because the past 40 years represents only one of potentially many realisations that could have unfolded in the past, and the following calculation is made only for cereals. According to the agricultural statistics of the FAO (Food and Agriculture Organisation of the United Nations) (www.FAO.org), the total area of cereals has decreased from 42,657,095 ha in 1961 to 37,818,114 ha in 2000 (for example, see Rounsevell et al., 2003). The figure for the year 2000 includes, however, an area of land that was set-aside i.e. not used for cereal production, as part of the CAP arable area payment scheme. This comprised 5,714,300 ha in 2000. Thus, in practice, the cereal production area in 2000 was 32,103,814 ha or 0.75 times the production area in 1961.

This figure can be compared with a calculation made with the supply/demand model presented above. FAO figures indicate that in the year 2000, the demand for cereal products (human consumption, animal feed, processing, waste, etc.) was 1.59 times the demand in 1961. During the same time period technological change has increased cereal productivity (on average for Europe) from 2.6 to 5.27 t ha^{-1} a ratio of 0.49 (see Ewert et al., 2004). FAO data indicate that oversupply was unchanged from 1961 until 2000. Entered into Eq. (6), these figures give an estimated change factor of 0.78, which is consistent with the observed change of 0.75, indicated above.

4. Results

Fig. 2 shows that cropland areas decline substantially (to as much as 50% of current areas) by 2080 for the A1FI and A2 scenarios. Declines for the B1 scenario are less severe, and the smallest declines are for the B2 scenario. In this scenario cropland areas are assumed to be constant, and the declines shown in Fig. 2 represent the replacement of food production by bioenergy production. Declines in the grassland areas (see Fig. 3) for A1FI and A2 are even more marked (to <50% of current). Changes in grassland areas for B1 are the least severe because of assumed protection policies and the changes for B2 again reflect a switch from food to bioenergy production. Estimates of the bioenergy crop areas for B1 from the IMAGE model are less than for the B2 scenario because other forms of renewable energy sources are exploited in a B1 world.

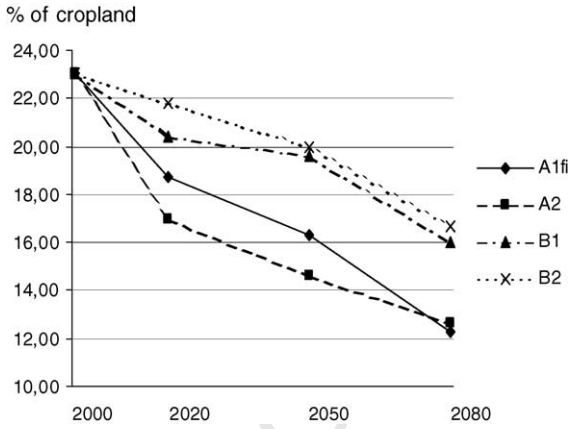

Fig. 2. Scenario changes in cropland areas for Europe (% of European area) for the HADCM3 GCM.

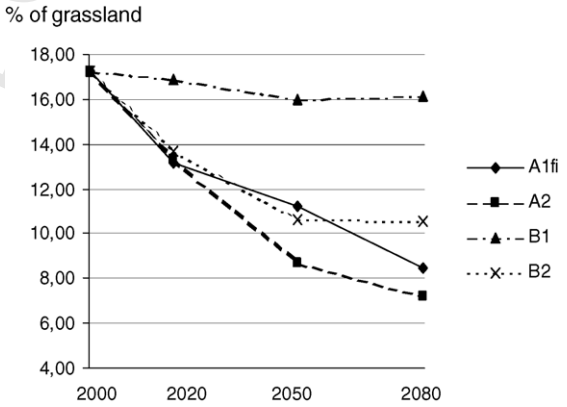

Fig. 3. Scenario changes in grassland areas for Europe (% of European area) for the HADCM3 GCM.

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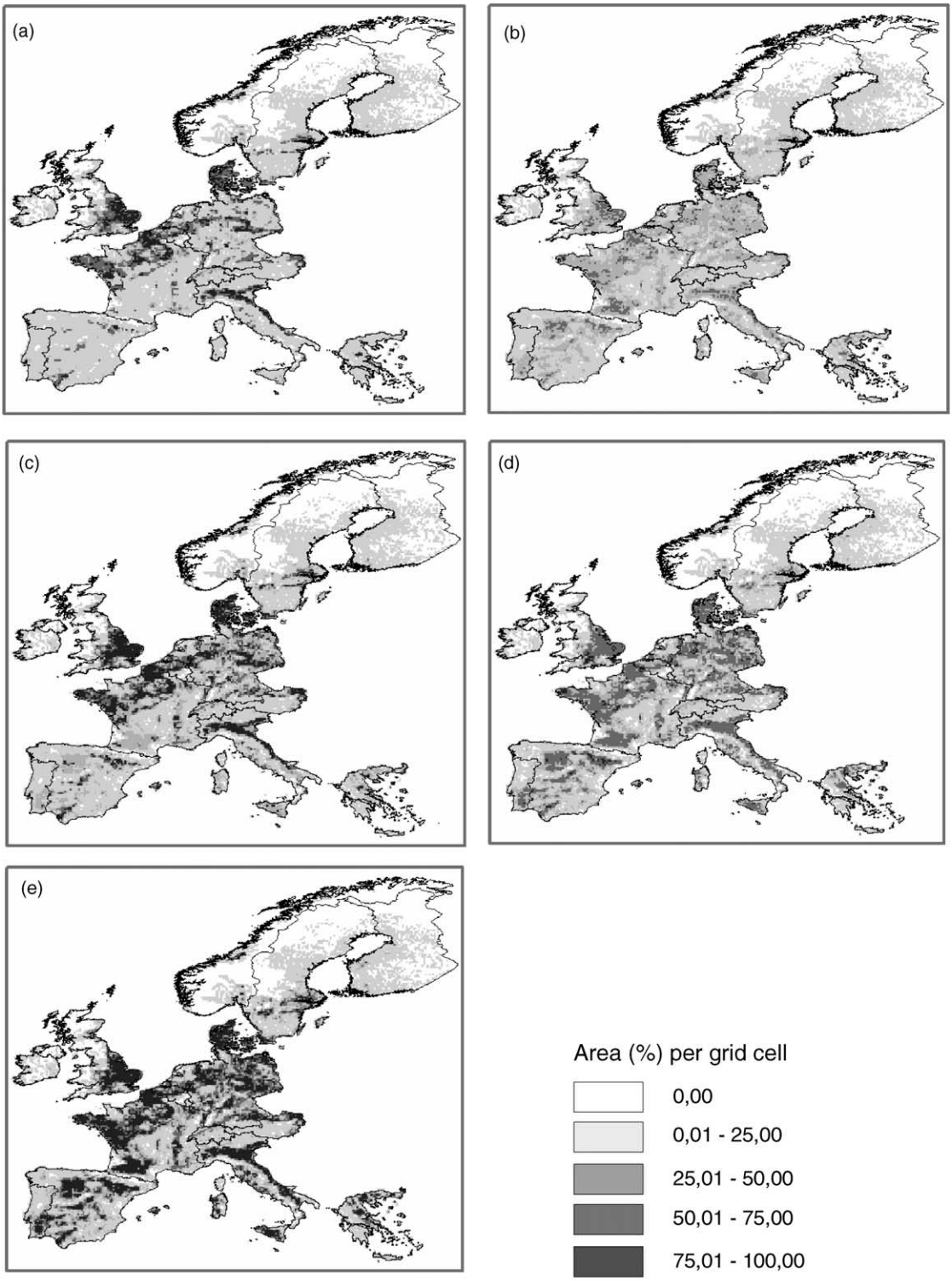
(a)
(b)
(c)
(d)
(e)
Area (%) per grid cell
0,00
0,01 - 25,00
25,01 - 50,00
50,01 - 75,00
75,01 - 100,00

Table 7
Pearson correlation coefficients for cropland and grassland scenarios

	A1FI 2080[a]	A2 2080[b]	B1 2080[c]	B2 2080[d]
Cropland				
Baseline	0.83**	0.98**	0.92**	0.98**
A2 2080	0.84**	1	0.92**	0.98**
B1 2080	0.96**	0.92**	1	0.93**
B2 2080	0.83**	0.98**	0.93**	1
Grassland				
Baseline	0.83**	0.92**	0.99**	0.88**
A2 2080	0.87**	1	0.92**	0.91**
B1 2080	0.83**	0.92**	1	0.90**
B2 2080	0.79**	0.91**	0.90**	1

[a] A1FI, global economic and fossil fuel intensive world.
[b] A2, regional economic world.
[c] B1, global environmental world.
[d] B2, regional environmental world.
** Indicates that the correlation is significant at the 0.01 level: 2-tailed.

Mapped examples of the different scenarios are presented in Figs. 4 and 5 for the HADCM3 (Hadley Centre) atmosphere–ocean general circulation model (GCM) (see Mitchell et al., in press). The scenario-specific, spatial allocation rules generate very different spatial patterns, which is especially evident when comparing the A1FI and A2 scenarios. Table 7 shows the Pearson correlation coefficients between the different scenarios in 2080 for both cropland and grassland. The Pearson correlation is a measure of global spatial patterns. For example, whilst the A2 scenario is very different from the baseline in terms of the (quantity) of land use areas, it has a similar spatial pattern, as indicated by the high correlation coefficients in Table 7. Conversely, the A1FI scenario has low correlation coefficients with respect to the other scenarios and is, therefore, spatially quite different. The low correlations of the B2 scenario reflect the substitution of food production by bioenergy production. The correlations between all scenarios are statistically significant. This is not surprising given that each scenario is derived from the same observed baseline.

Tables 8 and 9 provide a breakdown of the scenario results by country for cropland and grassland in 2080. The countries are presented in order of their cropland and grassland areas for the baseline. The table shows that for the A1FI scenario the country changes are strongly dependent on the LFA area. Thus, countries in the south of Europe, such as Spain (−74%), Portugal (−73%) and Greece (−68%) experience very large declines in agricultural areas that are much greater than the European-wide changes presented in Figs. 2 and 3. This reflects the potential for regional disparities within a globally orientated scenario. Conversely, the A2 scenario shows very similar changes between countries. The B1 scenario shows regional differences, but these are less pronounced than A1FI, and B2 shows the changes that are due to the widespread introduction of bioenergy crops. Fig. 6 shows the results for the A2 scenario of applying different climate scenarios based on a range of GCMs. There appear to be very few differences between these scenarios, which indicates that the socio-economic assumptions have a much greater effect on the scenario results then the climate scenarios.

5. Discussion

5.1. Scenario changes at the European scale

The large declines in the surface areas of agricultural land use for the A (economic) scenarios are caused primarily by the relatively low increases in demand and the far-reaching assumptions about the role of technological development. This represents a substantial change in European agricultural landscapes and raises the possibility of land being surplus to agricultural requirements. At first sight the scenarios appear extreme in this respect. In fact, the assumptions about technology development refer to wheat and future technology advances are likely to be less pronounced for other crops. However, wheat is the most important crop in Europe, which is unlikely to change in the future. Also, as shown above, the agricultural area of Europe has already diminished by about 13% in the 40 years since 1960 and this within a policy framework that has sought both to increase production and production areas (in the early years of

Fig. 4. Cropland areas (for food production) for Europe (10 ft × 10 ft resolution) in 2080 for the scenarios: (a) A1FI HADCM3, (b) A2 HADCM3, (c) B1 HADCM3, (d) B2 HADCM3, and (e) the baseline (2000).

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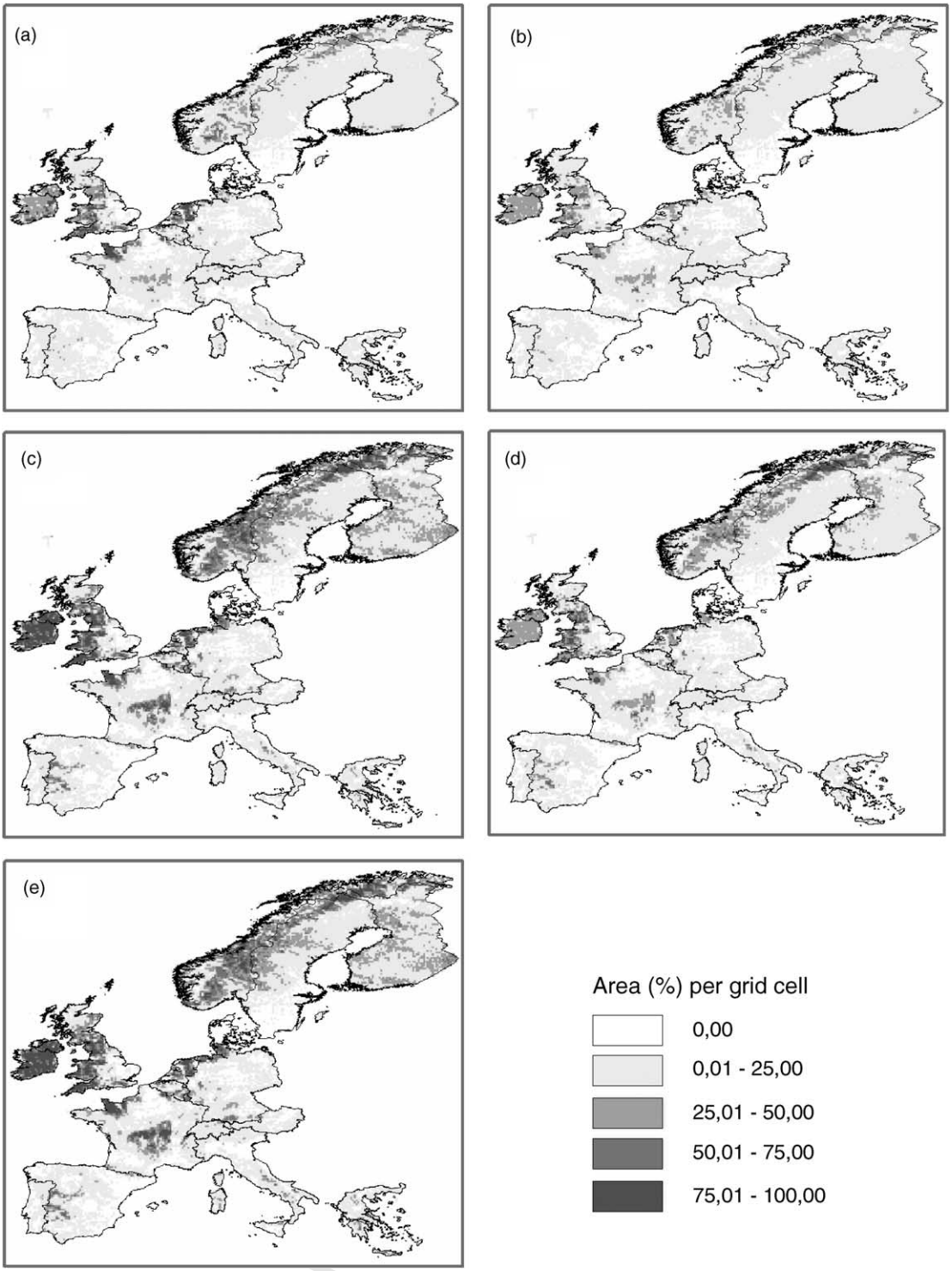

Fig. 5. Grassland areas (for food production) for Europe (10 ft × 10 ft resolution) in 2080 for the scenarios: (a) A1FI HADCM3, (b) A2 HADCM3, (c) B1 HADCM3, (d) B2 HADCM3, and (e) the baseline (2000).

Table 8
Comparison of regional means between the scenarios for cropland in 2080

	LFA (%)	Baseline	A1FI 2080 (%)[a]	A2 2080 (%)[b]	B1 2080 (%)[c]	B2 2080 (%)[d]
Denmark	0.00	59.32	49.35 (−17)	31.31 (−47)	54.50 (−8)	42.42 (−28)
Germany	54.97	48.66	25.59 (−47)	26.63 (−45)	36.03 −26)	36.54 (−25)
Belgium	25.73	46.04	36.79 (−20)	24.14 (−48)	40.56 (−12)	32.39 (−30)
France	50.79	45.87	26.70 (−42)	24.71 (−46)	32.91 (−28)	32.52 (−29)
Italy	60.53	39.53	20.13 (−49)	20.87 (−47)	25.57 (−35)	27.21 (−21)
Spain	80.22	33.17	8.78 (−74)	17.54 (−47)	17.23 (−48)	23.69 (−29)
The Netherlands	0.35	33.08	27.46 (−17)	18.04 (−45)	29.92 (−10)	25.44 (−23)
Austria	75.03	28.70	14.39 (−50)	15.42 (−46)	20.35 (−29)	21.18 (−26)
Portugal	81.64	26.98	7.24 (−73)	14.22 (−47)	12.49 (−54)	17.23 (−36)
Greece	84.87	25.66	8.18 (−68)	13.50 (−47)	13.96 (−46)	17.30 (−33)
UK	48.78	25.05	19.75 (−21)	13.71 (−45)	22.43 (−10)	18.84 (−25)
Switzerland	81.15	22.34	13.12 (−41)	11.91 (−47)	17.59 (−21)	17.02 (−24)
Sweden	85.59	8.99	4.23 (−53)	4.71 (−48)	5.37 (−40)	6.05 (−33)
Luxembourg	100.00	8.00	2.06 (−74)	4.22 (−47)	3.61 (−55)	5.44 (−32)
Ireland	75.56	3.22	1.29 (−60)	1.67 (−48)	1.53 (−53)	1.95 (−40)
Finland	82.93	2.65	0.86 (−67)	1.39 (−47)	1.08 (−59)	1.74 (−34)
Norway	70.40	1.81	1.09 (−40)	0.95 (−48)	1.13 (−37)	1.21 (−33)
Europe+	68.68	23.02	12.27 (−47)	12.66 (−45)	16.01 (−30)	16.65 (−28)

[a] A1FI, global economic and fossil fuel intensive world.
[b] A2, regional economic world.
[c] B1, global environmental world.
[d] B2, regional environmental world.

Table 9
Comparison of regional means between the scenarios for grassland in 2080

	LFA (%)	Baseline	A1FI 2080[a]	A2 2080[b]	B1 2080[c]	B2 2080[d]
Ireland	75.56	63.26	27.47 (−57)	23.12 (−63)	60.22 (−5)	26.01 (−58)
Luxembourg	100.00	48.27	18.68 (−61)	19.82 (−58)	45.04 (−7)	26.40 (−45)
The Netherlands	0.35	36.17	35.70 (−1)	14.54 (−60)	33.42 (−8)	23.36 (−35)
Norway	70.40	34.94	14.71 (−58)	13.03 (−63)	34.72 (−1)	20.71 (−41)
UK	48.78	33.04	21.00 (−37)	15.29 (−54)	31.26 (−5)	21.18 (−36)
Belgium	25.73	22.35	16.52 (−26)	8.98 (−60)	19.21 (−14)	11.55 (−48)
Finland	82.93	20.92	8.84 (−58)	8.31 (−60)	20.91 (−0.05	12.97 (−38)
Sweden	85.59	17.51	7.47 (−57)	7.68 (−56)	17.50 (−0.06	12.65 (−28)
France	50.79	15.14	8.70 (−43)	6.22 (−59)	12.09 (−20)	7.85 (−48)
Switzerland	81.15	9.34	4.90 (−48)	3.66 (−61)	8.24 (−12)	6.53 (−30)
Germany	54.97	9.22	4.85 (−47)	4.07 (−56)	7.50 (−19)	5.43 (−41)
Greece	84.87	9.17	3.52 (−61)	3.38 (−63)	6.94 (−24)	4.65 (−49)
Italy	60.53	5.91	2.68 (−55)	2.46 (−58)	3.16 (−47)	3.36 (−43)
Spain	80.22	5.64	2.17 (−62)	2.18 (−61)	5.30 (−6)	4.22 (−25)
Austria	75.03	3.36	1.59 (−53)	1.40 (−58)	3.24 (−4)	2.15 (−36)
Portugal	81.64	2.87	1.08 (−62)	1.13 (−61)	1.40 (−51)	1.28 (−55)
Denmark	0.00	0.36	0.30 (−17)	0.13 (−64)	0.36 (−0)	0.17 (−53)
Europe+	68.68	17.23	8.50 (−51)	7.19 (−58)	16.17 (−6)	10.56 (−38)

[a] A1FI, global economic and fossil fuel intensive world.
[b] A2, regional economic world.
[c] B1, global environmental world.
[d] B2, regional environmental world.

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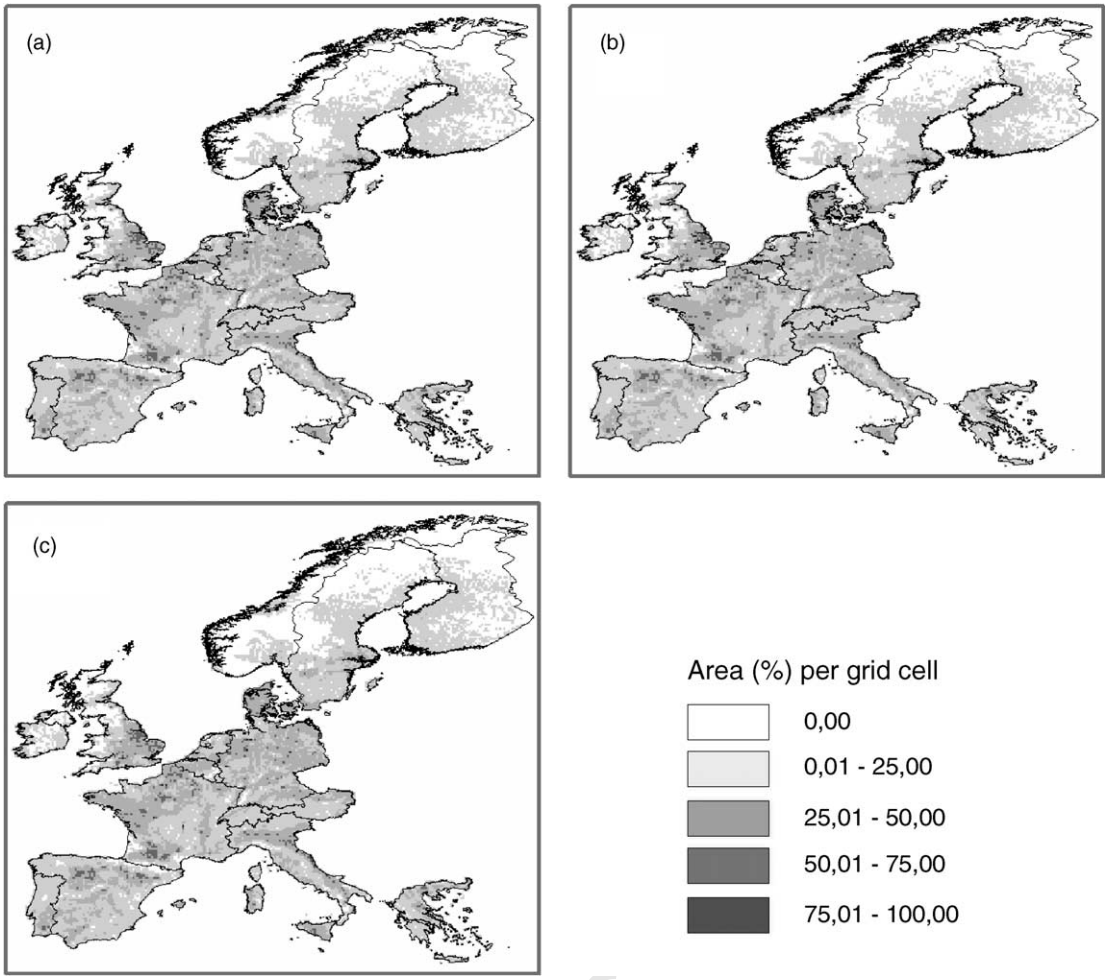

Fig. 6. Cropland areas for Europe (10 ft × 10 ft resolution) in 2080 for the A2 scenario and the GCMs: (a) PCM2, (b) CGCM2, and (c) CSIRO2.

the CAP) and latterly to maintain the status quo by subsidising marginal production areas. It is interesting to speculate how land areas would have changed in the absence of such interventionist policies.

It is unclear what would happen to the potential areas of surplus land, but continued urban expansion, recreational areas (including golf-courses and other sport utilities, fields for horse riding and camp sites) and forest land use are all likely to take up at least some of this surplus. Furthermore, the scenarios presented have assumed that in the future energy production will widely substitute for food production, especially if further gains are made in the technology of bioenergy production. Thus, bioenergy production takes-up a certain proportion of the land that would be surplus to requirement assuming food and fibre production only. It would be interesting to analyse further the prospects for bioenergy production given the potential availability of agricultural land areas.

The existence of surplus areas also takes no account of the potential for structural changes in the farming sector. For example, the current trend in Europe of increasing farm sizes with fewer farmers, might represent an appropriate adaptation strategy to land use change pressures. The land use declines presented here suggest that the supply of agricultural goods in the future will outstrip demand. This implies (although it is not explicitly modelled) that the relative price of

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goods and gross margins would fall. One way of responding to such a situation is to increase production areas to maintain profitability in the face of lower income per unit area. This is often seen in extensive production areas. Thus, increases in farm sizes and a move to extensification with correspondingly smaller declines in land use areas might be a logical consequence of the types of economic pressures implied for the A scenarios.

It is possible that a certain level of policy intervention would always occur, even within the A scenarios, in order to maintain the European production of certain agricultural goods as a 'buffer' against external market fluctuations and production changes. Self-sufficiency was one of the principal objectives of the original CAP market mechanisms (Rounsevell et al., 2003). Such intervention would consequently reduce the modelled areas of surplus agricultural land by acting on the oversupply parameter. It is worth noting that the scenarios presented here are strongly dependant on the modest changes in demand figures derived from the IMAGE model (cf. Table 2). Most demands initially increase but decline later this century. Larger or continuous increases or decreases in these parameter values would give quite different scenario outcomes in terms of land use areas.

Declines in agricultural areas are less 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 extensification or organic production (particularly consistent in the environmental scenarios), an acceptance of overproduction (as with the current CAP) or the management of land for conservation goals. It is difficult to estimate whether in practice such intervention strategies would be possible given the potential for high costs and diminished competitiveness. As indicated above, even in the highly protective CAP system, agricultural areas have decreased by almost 13% over the last 40 years (Rounsevell et al., 2003). Furthermore, such problems would be exacerbated if more rapid technological development occurred within a protectionist policy strategy because of the stimulation of innovation.

Whichever scenario is considered, however, the work presented here suggests that it is likely that agriculture in Europe in the future will be managed in more diverse ways, with changes from food to energy production, extensification and the provision of landscape (conservation and/or recreation) services.

5.2. Spatial changes

It should be noted that the use of the LFA map to identify 'optimal' agricultural production areas whilst pragmatic, is not ideal. In some cases it appears that the designation of LFAs is based as much on politics as on a true valuation of the production capacity of a location. Furthermore, in using LFAs, no account is taken of regional differences in prices and costs that also contribute to the economic viability of agricultural production. The implications of the scenarios presented in Figs. 4 and 5 are very important for future policy formulation. It appears that many parts of Europe would need to be protected from world markets in order to maintain agricultural production and rural communities, as largely happens today. However, the consequences of providing regional protectionism imply that more productive production areas would suffer in consequence. There are also implications for international trade negotiations, notably through the WTO.

When examining Fig. 6 care should be taken in drawing firm conclusions from the apparent lack of sensitivity of agricultural land use to climate change. At the regional scale there are winners and losers (in terms of yield changes), but these tend to cancel each other out when aggregated to the whole of Europe. Thus, the results suggest that at the European scale, crop productivity is not sensitive to climate change, whereas at the regional scale it could be very sensitive to climate change (depending on the region in question). Furthermore, the methods for calculating cropland and grassland yields used here were highly simplified. Taking 'proxy' crops does not account for the diversity of agricultural production strategies that could be possible in practice. The approach is also based on long-term mean productivity levels, and does not account for the effects of yield variability (e.g. arising from future climate variability), which are known to affect decisions about agricultural land use (Rounsevell et al., 2003). An alternative to the proxy approach is to model the yield response of each individual crop and the competition between them, which is not feasible at the scale of this analysis as it would require detailed management

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information as well as agricultural commodity prices and costs. This would also over-complicate a modelling approach that is intended to be simple and transparent. One of the consequences of developing scenarios at the European scale is that regional-scale processes are difficult to represent.

An attempt was made to validate the quantity of land use change against historic data, but it was not possible to validate the spatial patterns that result from the spatial allocation rules within each scenario. The reason for this is that historic land use data (against which a validation can be undertaken) represent only one possible realisation of the past, i.e. one set of circumstances (of economic development, policy formulation, etc), that has resulted in the pattern of land use that is observed today. If, hypothetically, the past could be 're-run' with different economic and policy conditions then the observed land use patterns would be different. As these alternative realisations do not exist, however, there is no observation against which a validation of the alternative assumptions could be undertaken. Furthermore, calibrating spatial allocation algorithms against past land use patterns may be flawed as such algorithms only ever produce future scenarios with spatial patterns that mirror history. They are unable to account for future changes in land use patterns that depend on processes that are very different from those that occurred in the past.

6. Conclusions

Scenarios are themselves models of how the real world functions and like other types of models they allow explorations of understanding. The construction of the scenarios presented in this article has demonstrated the importance of assumptions about technological development for future agricultural land use in Europe. If technology continues to progress at current rates (i.e. since the 1960s) then the area of agricultural land would need to decline substantially. Such declines will not occur if there is a correspondingly large increase in the demand for agricultural goods, or if political decisions are taken either to reduce crop productivity through policies that encourage extensification or to accept widespread overproduction.

For the set of parameters assumed here, cropland and grassland areas (for the production of food and fibre) decline by as much as 50% of current areas for some scenarios. Such declines in production areas would result in large parts of Europe becoming surplus to the requirement of food and fibre production. Although it is difficult to anticipate how this land would be used in the future, it seems that continued urban expansion, recreational areas and forest land use would all be likely to take up at least some of the surplus. Furthermore, surplus land provides potential opportunities for the substitution of food production by energy production through the widespread cultivation of bioenergy crops.

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