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RESEARCH ARTICLE

An agent-based approach to modeling impacts of agricultural policy on land use, biodiversity and ecosystem services

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Abstract We present extensions to the agent-based agricultural policy simulator (AgriPoliS) model that make it possible to simulate the consequences of agricultural policy reform on farmers' land use decisions and concomitant impacts on landscape mosaic, biodiversity and ecosystem services in a real agricultural region. An observed population of farms is modelled as a multi-agent system where individual farm-agent behaviour and their interactions—principally competition for land—are defined through an optimization framework with land use and landscape impacts resulting as emergent properties of the system. The model is calibrated to real data on the farms and the landscape to be studied. We illustrate the utility of the model by evaluating the potential impacts of three alternative frameworks for the European Union Common Agricultural Policy (CAP) on landscape values in two marginal agricultural regions. Mosaic value was found to be sensitive to the choice of policy scheme in one of the landscapes, whereas significant trade-offs were shown to occur in terms of species richness by habitat and species composition at the landscape scale in both regions. The relationship between food production and other ecosystem services was found to be multifaceted. Thus illustrating the difficulty of achieving landscape goals in a particular region with simple or general land management rules (such as the current rules attached to CAPs direct payments). Given the scarcity of funding for conservation, the level and conditions for allocating direct payments are, potentially, of great importance for preserving landscape values in marginal agricultural regions (subject to levels of other support).

Keywords Agent-based modeling (ABM) · Landscape · Policy · CAP · Agriculture · Farming · Biodiversity

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Introduction

Characteristic of Europe is its variety of historical agricultural landscapes that echo a rich cultural heritage, provide habitat for a wide range of species and generate a broad range of ecosystem services (Benton et al. 2003; Swinton et al. 2007). These landscapes—principally those with a fine-grained mosaic and low-intensity/extensive production systems—have evolved over centuries in interaction with humans and provide semi-natural habitat for many endangered and rare species that are dependent on continued management for their preservation (Edwards et al. 1999; Billeter et al. 2008; Kleijn et al. 2009). Abandonment of farmland in many extensive areas of Europe therefore represents a threat to conservation rather than an opportunity for a return to nature. Central to the fate of these landscapes are the daily decisions made by thousands of individual farmers such as what commodities to produce, how to manage land and, in the long term, whether to continue farming and managing the landscape, or leave the sector. Whilst the actions of any single farmer might be of little consequence, as a group, farmers shape the landscape and control habitat important for conservation (Scherr and McNeely 2008). Factors that influence farm profitability and hence production decisions can therefore have profound effects on the landscape, biodiversity and ecosystem services.

A major influence on farming in the European Union (EU) is the Common Agricultural Policy (CAP) which is subject to regular reform. Most recently the requirement to produce commodities in return for support was abolished in the 2003 or *decoupling* reform which was implemented in 2005. Instead of receiving a subsidy per unit of commodity output (e.g. €200/ha wheat or €100/head of livestock which leads to surplus production) EU farmers now receive direct payments based on a Single Payment Scheme not related to the level of output (e.g., €200/ha agricultural land). To claim decoupled payments agricultural land is required to be kept in "Good Agricultural and Environmental Condition" (GAEC). In its simplest form GAEC implies mowing grass-sown fallow fields on an annual basis, and respecting relevant Statutory Management Requirements, together referred to as cross-compliance. As a result farmers' output decisions in the EU are now—for the most part—guided by market forces and not distorted by output subsidies (OECD 2001). The next CAP programme period, 2013–2020, is to follow the same basic principles for entitlement to support, but with the ambition to make it "greener" by placing additional environmental obligations on farmers in return for support (EC 2011).

A natural consequence of decoupling, all other things equal, is that traditional agricultural activities necessary for the preservation of landscapes might decline (e.g. grazing livestock to preserve meadows), particularly in low-intensive areas. On the other hand the total CAP budget is largely unchanged: each year approximately €40 billion is transferred to farmers and land owners in the form of decoupled payments and another €14 billion in the form of Rural Development Programme payments such as agri-environmental schemes (EU 2009). Despite these enormous sums and goals for environmental protection it can be very difficult to determine the potential consequences of policy reform for landscapes and biodiversity due to a lack of suitable evaluation tools (Kleijn et al. 2006; Knop et al. 2006).

The aims of this article are as follows: First, we extend an existing agent-based model (ABM) of agriculture—the agricultural policy simulator (AgriPoliS) model (Balmann 1997; Happe et al. 2006)—to analyse the impacts of changes in agricultural policy on land use, biodiversity and ecosystem services in a real agricultural region, up to 25 years into the future. Secondly, the extended model is used to evaluate the potential environmental impacts of CAP reform in two low-intensive regions in the EU. By relating farm structure (a pattern) as affected by processes at different scales (i.e. policy formulation and individual farm-agent decisions) we hope also to contribute to better understanding of the sustainability of low-intensive agricultural landscapes (Wu 2006).

In human dominated, low-intensive landscapes in the EU, the continuation of specific management actions is critical for the conservation of species and ecosystem services (e.g. Donald et al. 2001). The probability that farmers continue with desirable behaviour is however determined by the interaction of factors at different scales: from price determination in global markets, to policy at EU and regional levels, and ultimately landscape and field specific characteristics. With AgriPoliS it is possible to evaluate the impacts of micro or farm level decision making at a relatively large scale (e.g. province or county). This scale is large enough to be relevant for policy analysis and informing decision making (e.g. Brady et al. 2011), and hence represents an increase in the utility of the ABM approach that has previously been regarded primarily as a research tool rather than providing decision support (Matthews et al. 2007). Specifically, modelling the entire population of farms at this scale and in detail can be used to link the dynamics of farm structure (changes in number and sizes of farms) to landscape dynamics and thereby bridge a gap to large scale land use models (e.g. Verburg and Overmars 2009). The state of each individual plot in the landscape is determined by the result of individual farm-agents' optimizing behaviour—and consequently each of the factors affecting their objective function—rather than by transitional probabilities (e.g. Turner 1987). In this way we incorporate a number of the complexities of the agri-ecological system into a cohesive spatial framework (Cumming 2011). Particularly important in this context are non-monetary aspects such as land productivity, field size and proximity, and hence how spatial heterogeneity influences the outcomes of policy (the focus of this study).

In the next section we present our agent-based approach to landscape modelling and describe how the model is calibrated to a real landscape. In the "Results" section we assess the potential impacts of three alternative policy schemes in two study landscapes. We conclude with a discussion of the implications of CAP reform for conservation of landscapes and biodiversity, and the utility of our approach for policy analysis.

Methods and theory

In order to predict or simulate the impacts of agricultural policy reform on the landscape it is necessary to model farmer behaviour and link possible decisions to outcomes. There is a long tradition of system scale modelling in agricultural economics—from individual farmer behaviour to the global level—to evaluate the impacts of changes in policy and other drivers on agricultural prices and output (Nelson et al. 2011). These models have been further developed for analysing environmental impacts (Just and Antle 1990; Vatn et al. 1999), landscape aspects (Wu et al. 2004; Antle and Valdivia 2006) and ecosystem services (Antle et al. 2007; Wossink and Swinton 2007). Application of the agent-based approach to modelling farmer behaviour and landscape dynamics is relatively new (Balmann 1997; Berger 2001; Happe et al. 2008). A key advantage of an ABM compared to other economic models is the capacity to represent heterogeneity amongst farms and land, and model decision making from the bottom up (i.e. locally interacting farms competing for land) so that emergent properties of the system can be analyzed at an aggregate level such as the region or landscape (Lansing and Kremer 1993; Axtell et al. 2002; Parker et al. 2003; Happe et al. 2006; Janssen and Ostrom 2006; Fontaine and Rounsevell 2009). Here we extend the ABM AgriPoliS, for modelling landscape values. AgriPoliS is normally used to analyse regional structural change in agriculture (Balmann 1997; Happe et al. 2006). The following model description follows the ODD protocol (for Overview, Design concepts and Details of ABMs) presented in Grimm et al. (2006, 2010). The description is condensed but describes the most relevant factors driving land use change and landscape indicators in the model. The focus is on the extensions by specific sub-models. A comprehensive description of AgriPoliS can be found in Kellermann et al. (2008).

Overview and design of the ABM AgriPoliS

The *purpose* of AgriPoliS is to understand how the income maximizing behaviour of thousands of individual farm-agents competing for heterogeneous land on a finite landscape affects structural change within a region depending on the agricultural policy. AgriPoliS covers changes in farm size, farm exits and changes in production. Farm expansion associated with growth in field size and changes in production affect landscape mosaic and biodiversity.

The model's *main entities* are farms, production activities, investment objects, plots, markets, and the political environment. The key *state variables* associated with each farm-agent in the model are: (a) quantity and age of fixed-assets, i.e. machinery and buildings, (b) area of owned and rented land, (c) equity capital, (d) amount of family labour, (e) farmers' age and (f) managerial ability. Together these variables determine the "fitness" of a farm-agent to finance investments and win land on the auction market; and hence produce profitably and survive. To maximize net family income farms choose from a list of production activities and investment options in order to optimally use their resource endowments (land, family labour, liquid capital and fixed-assets).

Production activities can be further differentiated into plant and livestock activities, and auxiliary activities (saving/borrowing, working off-farm, hiring labour and agri-services). Plant and livestock production activities are characterised by a revenue (price $\times$ yield), production costs, a labour requirement and associated policy payments. Only revenues and payments can change over time due to changes in the political environment. For the biodiversity analysis the state variables for plant production activities have been extended for modelling species richness (see below).

Plots are the basic elements of the grid representing an artificial landscape. The state variables of these basic land units are size, location, soil type, ownership, rental price, rental contract duration and age of the contract. Location, size and soil type of a plot are constant during the simulations whereas the ownership status, the rental price and the age of the contract can change over time. As a soil type we define land of a specific quality (e.g. high, medium, low, etc.). Depending on the quality, land can only be used for specific production activities and generate a particular yield. Thereby, we indirectly differentiate between arable land, grassland and non-agricultural land (settlements, roads, rivers, lakes and forests that cannot be used for agriculture). The ownership status of plots is either "owned", "rented" or "abandoned". Rental prices can change during simulations because an endogenous rental market is modelled. Rental contracts have a fixed duration and are terminated when the age of the contract equals the duration. Taken together, the location of the plots, their size, the soil type and the ownership form a basic artificial landscape with contiguous plots of a specific soil type owned or rented by a specific farm. The allocation of each farms' production to their plots further defines the landscape.

Markets modelled endogenously are regional markets for dairy calves, milk quota, manure and land. Prices of internationally traded products (grains, meat, etc.) and inputs (fertilizer, energy, etc.) are kept constant—in any particular simulation year— because changes in production in small regions are unlikely to affect prices. The markets for calves and milk quota are modelled considering demand and supply and the land market is modelled as an auction. The land market is the central point of interaction between agents: for one farm to grow another must close or down-size—and thereby release land to the market—since the total land area is a limited resource. This market is spatially explicit in that land quality, field size and distance costs to the farm centre are included in the farm-agents' valuation of the plots.

Scales in the model are as follows: Plot size is set at a resolution relevant for the landscape being studied, typically 0.5–5 ha, and the largest landscape modelled so far is around 1.7 million ha. Agricultural decisions are modelled on an annual basis hence the time-step in simulations is 1 year with a maximum length of 25 years.

The model includes two phases: (i) the model structure is created in the initialisation phase. This includes the creation of farm-agents and the model landscape. The sub-model for the *Landscape initialisation* has been extended for this study and is explained below; (ii) In the simulation phase the following processes are repeated in each simulation period: first, the Auctioneer agent instigates the *land auction* to allocate unused land to farm-agents. On completion of the land auction, farm-agents have the possibility of *investing* in new machinery or buildings. They then decide what to *produce* by optimally using their resource endowments to maximize their household income. Based on the amount of produced products, prices on regional *markets are updated*. The actual prices are then considered in *farm-agents' accounting*. Then farmers receive *information about the policy* for the next year and their *resource endowments are updated*, i.e. plots with terminating rental contracts are released to the land market and investment objects at the end of their useful life are withdrawn from the list of resource endowments. At the end of each simulation period the farm-agents *decide whether to continue farming or exit*. For this decision, farm-agents calculate on the one hand their expected income from agriculture considering changes in the policy and their resource endowments. On the other hand they take into account all adjustment opportunities offered by exiting agriculture such as off-farm labour, leasing own land to other farmers and saving money previously used for agricultural production. The farm exits agriculture if the income provided by opportunities outside agriculture are greater than the expected income from agriculture. For the land auction, investment, production and exit decision farm-agents apply a Mixed Integer Programming model (cf. Hazell and Norton 1986) in order to optimize their decisions at each step. At the end of each period, the accounting, production and investments of each farm-agent are written to *output* files as well as aggregated data for the region as a whole. To evaluate the landscape, the production of each farm is allocated to the farm's plots (see sub-model *Allocation of production to plots*). Based on the land use and the allocation of production to plots, which change depending on farm-agent's production decisions and depending on the rate of farm growth, two *Landscape indicators* are calculated to evaluate mosaic, the: (i) Shannon–Wiener Index to measure the diversity and distribution of land uses and (ii) average field size. Field size is likely to increase depending on the rate of farm growth. Finally the species–area relationship is used to calculate a *Biodiversity indicator*. The simulation terminates when the number of specified simulation periods is reached.

In AgriPoliS the following *design concepts* are considered: Farm population and landscape dynamics *emerge* from the optimizing behaviour of individual farm-agents. Optimization is handled using mathematical programming (which also provides a practical framework for linking economic, ecological and biophysical elements of the agricultural system). Farm-agents can *adapt* to changing conditions by altering their production (according to possibilities typical for the region) or land use, investing to reduce unit production costs, renting more land to realize scale economies, adjusting their level of on-farm labour or quit farming. As far as *predicting* the future, decision making is myopic and follows adaptive expectations: policy changes and prices are anticipated only 1 year in advance. Further, farm-agents *know* only their own status except for the land rent information provided by the Auctioneer. They *interact* by competing for agricultural land on the endogenous land market.

For the *initialization*, data about the landscape needs to be collected (distribution of different types of agricultural land, the agricultural structure of the study region, farms located in the region, characteristic production activities and investment options, the number of threatened species and habitat areas, and general economic indicators). Data about the distribution of field size and landscape fragmentation are used as goal parameters to represent the real landscape which is described in the sub-model *Landscape initialisation*.

By using data about the agricultural structure of a region such as the number of farms, livestock, total amount of land of different qualities, number of farms in specific size classes, etc. and a sample of farms from the study region, a farm population is created that is representative of the observed structure of agriculture. During the initialisation of AgriPoliS the selected farms are cloned according to their up-scaling factors. Subsequently the cloned farms are individualized, meaning that they are differentiated randomly with respect to their location, the farmer's age, managerial ability, vintage of investments and the duration of each plot's rental contract.

Data about production activities and investment objects are obtained from relevant sources e.g. farm management pocket books or advisory services. In order to fit the selected farms' optimized production levels to observed levels they have to be calibrated (using standard farm modelling techniques) before initialisation in AgriPoliS. Similarly the number of species per plant production activity necessary for the biodiversity analysis should come from relevant sources (e.g. inventories of threatened species by land use).

Changes in the policy framework and price changes caused by changes in the policy itself are the only *input* during a simulation run. They comprise changes in the level of policy payments and conditions for receiving payments, and changes in exogenous prices (i.e. that are predicted by other models and fed into AgriPoliS if need be).

Sub-models

Landscape initialization

A natural way of considering the spatial environment of a farm is to use GIS. However, while spatial data might be available through e.g. remote sensing, it is usually not possible to obtain socio-economic information about spatially explicit farms because survey data is usually unidentified for privacy reasons. Instead we generate a statistical or abstract model of the landscape. This approach captures some important characteristics of the real landscape (field size distribution and fragmentation) while other characteristics are ignored (field shape). The abstract landscape can be used to answer questions related to these characteristics (Saura and Martinez-Millan 2000; Li et al.

2004). Even synthetic landscapes that are not calibrated to any specific landscape can be used for studying landscapes (O'Neill et al. 1992; With 1997).

Space in AgriPoliS is represented by a 2-dimensional grid of equally-sized cells or plots. Each plot represents a homogenous unit of land, i.e. land type, which can be assigned different characteristics relevant for farm-agents or landscape features (e.g. soil properties). Any number of different land types can be defined, however all aspects of the landscape not expected to change as a result of agricultural policy such as forests, lakes, built-up areas, etc., are subsumed into a single land or plot type, *non-agricultural land*. The non-agricultural area is subsequently fixed during simulations (this is not a model limitation but an assumption about the probability of land being converted to farmland). In the forthcoming simulations the areas of arable land and permanent grassland/meadow are variable or endogenous. Further, the road network is not represented on the grid: transport costs for moving machinery or outputs are therefore calculated as a function of the Euclidean distance of farm-blocks to *farm centres* and a constant representing the average costs of transportation per km in the region. By farm centre we mean the point on the grid where a farm-agent's buildings are located and hence where machinery and livestock are kept, and produce delivered.

Since we are impelled to consider a finite landscape it is necessary to draw a landscape boundary which implies that spatial phenomenon outside the selected area are ignored. Farms on the edge of the model landscape are therefore not necessarily isolated but will be situated in proximity to farms in neighbouring regions and therefore have equal chance of survival as farms located more centrally in the study landscape. To eliminate this potential bias, farm-agents perceive the landscape as being borderless, i.e. a torus where plots located on the landscape border are modelled as being adjacent with plots on the opposite border. This is a common approach to dealing with edge effects of finite landscape models but may give biased results for non-random patterns (Haase 1995).

Currently five different grid layers are used to represent the structure of agriculture and the landscape, but additional layers could be introduced. These layers are illustrated in Fig. 1. Figure 1a shows the basic representation of the landscape in AgriPoliS as a two dimensional grid, in this case 10 × 10, with cells of equal size and a resolution appropriate for the

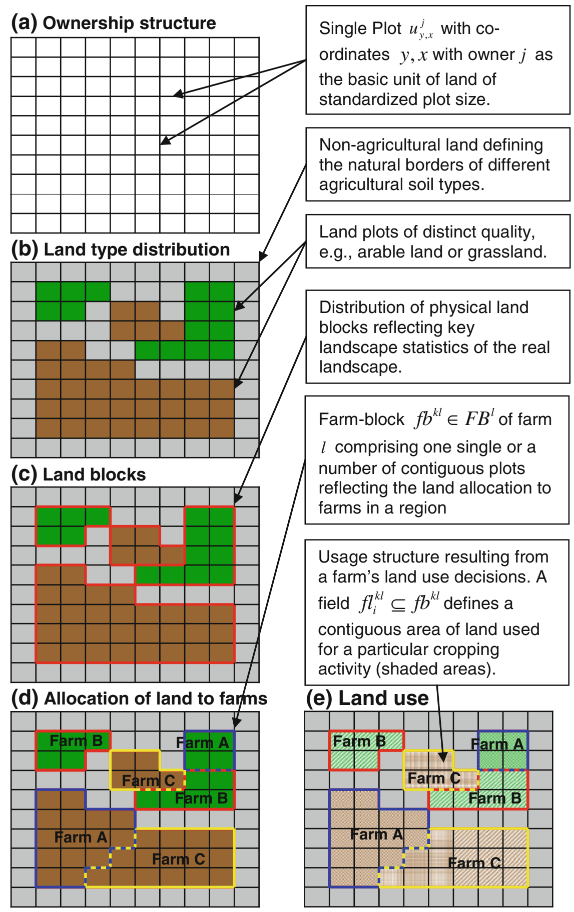

Fig. 1 Abstract landscape representation in AgriPoliS

landscape under study, which are indexed by their geographical coordinates (y, x) in the grid $\{Y, X\}$. Furthermore, this initial layer represents the ownership structure because each plot is owned by a farm-agent.

The second layer shown in Fig. 1b reflects the distribution of land types across the grid. In this example there are two agricultural land types; permanent grassland/meadow (green) and arable land (brown), and the remainder is classified as non-agricultural land (grey). Recall that land classified as non-agricultural is the area that is unlikely to be affected by farm-agents' production decisions and hence is assumed fixed during simulations.

The third layer represents permanent boundaries and replicates the distribution of agricultural land blocks, i.e., contiguous areas of a particular land type that are separated from other plots of the same type by either non-agricultural land or another land type, or protected by environmental legislation. Consequently these boundaries are fixed during simulations. In Fig. 1c the block layer is illustrated by two grassland blocks and two arable land blocks that are delineated by a thick red line. As such it is possible for multiple farms—as in reality—to own or rent the different plots comprising a block. Individual plots within a block can even take on different states of use, i.e. used for an agricultural activity according to the farm-agents' production possibility set or abandoned.

The layer shown in Fig. 1d represents the allocation of plots to farms and reflects farm-agents' land acquisition decisions via the *land auction*. Farm-blocks are therefore defined as a subset of contiguous plots within a block that are either owned or rented by the same farm-agent as illustrated by the six farm-blocks labelled Farm A, B or C in Fig. 1d. Consequently the distribution of farm-blocks defines the limits to field size expansion for individual farm-agents.

Finally, the fifth layer reflects a farm-agent's land use decisions (incorporating crop type and agricultural management practices) as it defines the fields, i.e. sets of contiguous plots, used by an agent for a particular activity (e.g. wheat produced using a specific technology) resulting from their optimal production decisions (defined below). Figure 1e illustrates the land use layer which can also be interpreted as the distribution of fields in the landscape. In this example Farm C's cropping decisions on its two farm-blocks result in three different fields comprising 5, 6 and 9 contiguous plots. Since the field structure is a result of the farm-agent's decision making it can change over time in response to changes in agricultural policy. For example field size can be increased by renting additional plots from neighbouring farms or growing fewer crops.

The distribution of block size for each soil type is controlled by varying the landscape initialisation parameters specified in Table 1. The basic procedure for initialising the landscape is as follows: Based on the selected farm sample, the necessary amount of land for each soil type is calculated, which is referred to as the *calculated number of plots* for each soil type. An appropriate plot size is also determined (e.g., median or mean field size). The amount of non-agricultural land is determined by the exogenous variable NON_AG_LAND. To influence the allocation of a specific type of plot to individual farms we define a buffer for each soil type so that more plots of each type are created than is actually needed to initialize the landscape. The higher the OVERSIZE factor the greater the chance of farms being allocated contiguous plots and hence having larger farm-blocks that are closer to the farm centre. The final number of plots in the virtual landscape where $i \in \{\text{NO\_OF\_SOILS}\}$ will be:

$$\text{OVERSIZE} \times \sum_i \text{calculated\_number\_of\_plots}_i \times (1 + \text{NON\_AG\_LAND}).$$

In the first step AgriPoliS distributes all defined land types and non-agricultural land over the grid to reflect the observed distributions of block size for each land type (achieved by varying the initialization parameters). Secondly a farm centre is randomly located in the grid for each farm-agent, and finally in an iterative process, each farm-agent selects a plot that is most valuable to the farm until each farm is endowed with its pre-defined allocation of land (plot value is determined by the same decision rule as for bidding in the land auction: if this rule was to minimise transportation costs, then the most valuable plot is the plot closest to the farm centre). Finally, any unallocated plots (equivalent to the OVERSIZE) are set to non-agricultural land.

Allocation of production to plots

Two additional properties of agricultural production are uniquely captured in our abstract landscape modelling; (i) spatially-explicit organisation and (ii)

Table 1 Overview of landscape initialization parameters

Parameter	Description	Range	Default
NO_OF_SOILS	Number of different soil types defined in a region	[1 to ∞]	2
PLOT_SIZE	Standard pixel size	[0 to ∞]	2.5
OVERSIZE	Share of additional land initialized in the region	[0 to ∞]	1.1
NON_AG_LAND	Share of non-agricultural land	[0 to ∞]	0.15

development of production patterns or land use as illustrated in Fig. 1. The next problem faced was to link multiple farm-agents' income maximizing production decisions—the behavioural foundation of the model—to cropping patterns in the landscape. In the mathematical programme used to model the optimizing behaviour of farm-agents, transportation costs, crop rotation requirements and field size are taken into account in the valuation of a plot. As such spatial aspects are implicit to the optimal production plan. Our method to derive an explicit spatial representation was to utilize the duality between the farmers' profit maximization problem and the associated cost-minimisation problem: As larger field sizes imply lower unit costs of production, minimising the costs of production for a crop implies maximising the field size of a particular activity within the constraints imposed by the size distribution of farm-blocks. Given this knowledge about how farmers frame their crop allocation decisions, we were able to model the allocation of crops to fields, and hence spread optimal levels of each production activity over the landscape in a fashion that is both similar to that of farmers in reality and is consistent with decision making in AgriPoliS. The algorithm is specified in Appendix S1 where 'S' indicates the *Supplementary material*.

Landscape indicators

The capacity to model land use as an emergent property of the interaction between individual farm-agents through space and time provides a basis for simulating and evaluating the impacts of changes in agricultural policy on landscape mosaic and biodiversity via changes in farm-agent behaviour. Mosaic is defined as the arrangement of fields in the landscape and their physiographic features that seen together seem to form a pattern; a distinctive landscape. To evaluate changes in mosaic we use three indicators. The first two are straight forward: changes in the areas of different land uses and mean field size (indicating myriad small or a few large fields). Mosaic value is intricately related to the *diversity* and *distribution* of land uses present in the landscape, hence to measure these characteristics we use the Shannon–Wiener Index

$$SWI = -\sum p_i \times \ln p_i \qquad (1)$$

where p_i is the proportion of the total land area covered by the ith land use. According to this indicator mosaic value increases if the area of a relatively scarce land use increases or a relatively common land use decreases (and vice versa). This is consistent with our understanding that European citizens prefer their historical mosaic landscapes compared to the more homogenous landscapes that result from industrializing agriculture (e.g. amalgamation of fields to make way for larger machinery). The more diverse and heterogeneous a landscape, the more complex its mosaic, and hence the more it can potentially contribute to amenity, recreational, cultural and knowledge values in the EU (Drake 1992; Lindborg et al. 2008; Sayadi et al. 2009). Increasing field size is also assumed to reduce mosaic value because larger fields result in more homogeneous blocks of a single land use.

Biodiversity indicator

To measure the consequences of changing land use on biodiversity we draw on the *species–area relationship* (Rosenzweig 1995), an approach also used by, e.g. Pereira and Daily (2006) and Nelson et al. (2009). Accordingly the number of species S_i supported by a particular habitat *i*, is modeled as a function of its total area A_i (ha) such that

$$S_i = c_i A_i^z \qquad (2)$$

where c_i is the species *productivity* of habitat *i* and z a scale parameter that determines how species productivity changes in response to habitat area. Typically z falls within a narrow range (0.18–0.25) for a diverse suite of ecosystems, therefore it is set to 0.19 in all simulations (Rosenzweig 1995). Since $z < 1$ the marginal diversity value of habitat is positive ($dS_i/dA_i > 0$) but decreasing in area ($d^2S_i \big/ dA_i^2 < 0$). Consequently *any* reduction in habitat area will be negative for its contribution to biodiversity—which follows common perception—but the strength of the impact will depend on the relative *scarcity* of the habitat and its species productivity c_i. The impact of a land use change at the landscape level on biodiversity could therefore be either positive or negative depending on the marginal biodiversity value of competing habitat. We assume that interdependencies exist between habitats of the *same* type because of the potential for species dispersal in a mosaic landscape. In a situation where the landscape becomes heavily degraded or fragmented, causing fields to become more and more isolated, an island approach to valuing diversity might be more appropriate.

Biodiversity value, from an economic perspective, is usually taken to comprise (i) genetic and species diversity, (ii) habitat and landscape diversity, (iii) ecosystem function and ecological service flows and (iv) existence values (Nunes et al. 2003). Fundamental to the nature of this value though is species diversity which is the number of *different* species. According to Weitzman (1992) a meaningful measure of the value of biodiversity should only consider species that are *unique* in some way. Simply counting the number of species or "richness" of a particular habitat is a poor measure of value in any sort of welfare context because it ignores the concept of marginal valuation and hence has no clear economic interpretation. It follows that *the marginal biodiversity value of an agricultural land use is its contribution of unique species to society and not those held in common with other land uses.* In the ensuing evaluation we use the number of threatened or red-listed species associated with a particular habitat as a proxy for the uniqueness of its species. To determine the unknown parameter c_i of the SAR for each habitat type Eq. 2 can be rearranged, and observations on threatened species S_i and habitat areas A_i plugged in, as follows:

$$c_i = \frac{S_i}{A_i^z}. \tag{3}$$

Study regions

Changes in agricultural policy are most likely to have landscape effects in marginal agricultural regions, particularly due to commodity production on less productive land being reliant on support. Consequently we selected two typical marginal regions for the study: the counties of Jönköping and Västerbotten in southern and northern Sweden respectively. Agricultural land use in both regions is dominated by grassland, with the combined areas of (rotational) arable grass land and meadow (semi-natural pasture) amounting to almost 80 % of the farmland area. Grains are primarily planted to maintain a crop rotation that avoids a decline in grass yields. The dominating agricultural output in both regions is milk followed by beef and lamb production. The data used for the regional representations can be found in Appendix S2 whereas details of the production and investment data can be found in Sahrbacher (2011).

Structure of agricultural production and the landscape

The structure of the study landscapes is illustrated in Fig. 2 where the shaded area is farmland and the remainder non-agricultural land (predominantly coniferous forest). In Jönköping agricultural land is interspersed between large areas of forest (Fig. 2a) whereas in Västerbotten it tends to be concentrated along valleys and hence is more connected (Fig. 2b). Consequently farmland is scarce habitat in both regions whereas forest habitat is abundant. The figures have been generated from the Swedish Board of Agriculture's Block-Database, data from which has also been used to initialize the virtual landscapes in AgriPoliS. The *landscape initialization* procedure is quite flexible and customizable down to the resolution of the land block. Hence the virtual landscapes agree well with the real landscapes based on the size distribution of blocks (see Appendix S3 for results).

If abandoned, farmland in Sweden becomes overgrown. Species richness may initially increase, but light-dependent species—principally vascular plants and the insects associated with them—are eventually displaced and the land reverts to forest (Bernes 1994). More than 2/3 of red-listed vascular plants in Sweden are found in agricultural landscapes (ArtDataBanken 2005). In addition, plants and animals that are dependent on old, thick stemmed deciduous trees growing on open sites (e.g. meadows) are adversely affected by afforestation whilst bird populations are sensitive to changes in agricultural land use per se (Donald et al. 2001). As a result, the decline in meadows and semi-natural or unimproved pastures over the past 50 years in Sweden has been particularly detrimental to species diversity (Lindborg et al. 2008). To improve agricultural efficiency, individual fields have also been amalgamated to make way for larger machinery. Many small scale habitats—such as ditches, headlands, islets of rough ground, ponds, etc. are therefore becoming increasingly rare with negative consequences for biodiversity (Benton et al. 2003). This context implies—according to our species–area model—that the marginal conservation value of an additional hectare of forest is close to zero whereas that of farmland, and in particular meadows, is high (see Appendix S4 for calibration of species–area relationships). In the case of forest species, they are more dependent for their survival

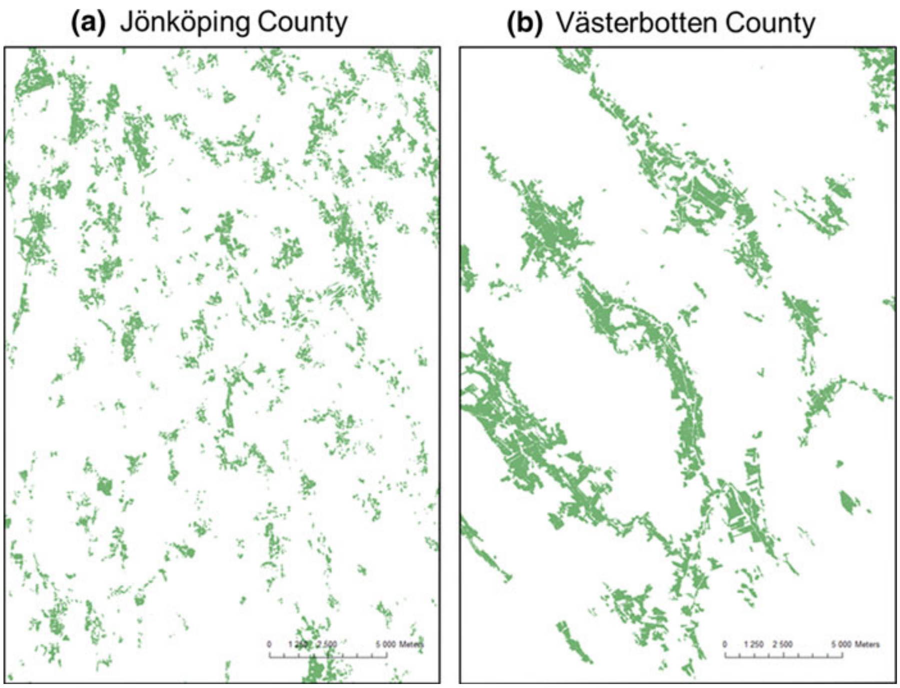

Fig. 2 Illustration of landscape structure in **a** Jönköping and **b** Västerbotten counties where agricultural land is shaded (the full length of each map scale is 5 km)

on forestry practices (the intensive margin) than afforestation on agricultural land (Berg et al. 1994).

For evaluating landscape mosaic we classify land use according to six categories relevant to the study regions: intensive grass silage, extensive grass silage, arable pasture, arable crops, meadow and forest. Arable pasture and silage refer to commercial grasses that are sown for producing animal fodder. Grass fallow that is mown but not harvested (e.g. to satisfy the minimum GAEC obligation) is classified as extensive silage due to their visual similarity. However, we distinguish between intensive and extensive silage because the larger numbers of labour and machinery hours associated with intensive production affect its aesthetic appeal since intensive fields are characterized by more *active* farming (Sayadi et al. 2009). For similar reasons arable pasture is assumed to have unique visual value due to the presence of livestock. Arable crops consist primarily of grain which has obvious visual dissimilarity to grass. Meadow in Sweden, as described above, hosts a large variety of wild grasses and flowers and can even be interspersed with solitary trees (typically oak or juniper) and hence has clear visual differences compared to arable habitats. Given the five possible agricultural land uses and the area of forest, the maximum possible value of the Shannon–Wiener Index for each landscape is 1.79 (i.e. $\ln 6$). Both landscapes had similar land use diversity in 2004 (i.e. the reference year before any policy change) according to this index; 1.32 for Jönköping and 1.39 for Västerbotten (see Table S5 for calculations). Since the proportion of each agricultural land use in the landscape is below a perfectly even distribution ($p_i = 0.17$) any reduction in an agricultural land use will reduce mosaic value as measured by the Shannon–Wiener Index.

The number of species by habitat for each region was obtained from the Swedish national database of species, maintained at the Swedish Species Information Centre (ArtDataBanken 2005). In this database every species with a Red List Category is described together with their occurrence in different administrative regions and habitat. In Appendix S5 we tabulate the number of species used to define S_i by region, species group and habitat, and the resulting coefficients used to calibrate Eq. 3 are reported in Table S8. Habitat areas were compiled in conjunction with calibration of the model landscape from published statistics. Since the species–area relationship (Eq. 2) is a homogeneous function of degree z, it is enough to have information about the relative values of c_i for different habitat in order to *rank* alternative land use patterns in terms of their contribution to biodiversity value (i.e. because the graphs of the functions never cross given some rescaling of c_i). This is important because the Swedish species inventories—like most inventories—are unlikely to have tallied all relevant species but provide an indication of relative species richness.

The marginal species value of habitat indicates how much total biodiversity would decline in each region given a reduction in a particular land use by 1 ha. By this measure, meadow in Västerbotten has the highest (marginal) value—because it is both a scarce habitat and has high species productivity—followed by meadow in Jönköping which has high species productivity but is relatively abundant (see Table S8 for calculations). Intensive silage has the lowest marginal value in both regions because it is not only relatively abundant habitat but also has low species productivity (e.g. due to fertilization and spraying). To calculate biodiversity at the landscape scale we assume that the habitat types; arable grass, arable crops and meadow, are additive in species because they support ostensibly different species pools. However, for the various arable grassland habitats the more species rich grass habits tend also to support the species found in the less rich habitats. The equations used to aggregate species across arable grassland habitat to avoid double-counting are derived in Appendix S5.

Results

Evaluated agricultural policy schemes

The extended AgriPoliS model is used to assess the potential impacts of three alternative agricultural policy *schemes* on landscape values in the study regions. Only direct payments or Pillar I income support (which comprises almost 80 % of the CAP budget) are varied in each scheme; existing Pillar II support such as environmental and compensation payments, and national support in Västerbotten are held constant throughout all simulations. Two "real world" policy schemes and a hypothetical scheme are simulated over the period 2004–2013 (i.e. until the next scheduled CAP reform). The AGENDA scheme represents continuation of the EUs Agenda 2000 framework or traditional agricultural support that is *coupled* to production. The principle ingredients of this scheme are payments based on the area of eligible crops and numbers of eligible livestock (i.e. cattle and sheep). The DECOUP scheme mirrors the Single Payment Scheme actually implemented in Sweden as a result of the 2005 CAP reform when support was *decoupled* from production. These payments are conditioned on land being kept in GAEC without the obligation to produce anything. At a minimum, GAEC involves mowing grass-sown arable land on an annual basis; meadows on the other hand must be grazed by livestock. Livestock payments are decoupled in two steps; in 2005 they are partially decoupled and in 2010 fully decoupled. The third scheme, FUTURE, is hypothetical and is designed to illustrate the implications of reducing direct payments (e.g. due to internal budget cuts or pressure from WTO) by around 30 %. This scheme is implemented in two steps: Initially direct payments are decoupled in 2005 according to the DECOUP scheme payment levels for each region in 2005; next, the decoupled direct payments for arable land are reduced to 99 €/ha over the period 2006–2013. The partially decoupled livestock payments are completely phased out during that period. To alleviate the extreme environmental consequences that phasing out of coupled livestock payments would entail (based on scoping simulations) we top-up the area payment for meadow by 66 €/ha in Jönköping and 25 €/ha in Västerbotten so that together with the existing environmental payments the total payment for meadow amounts to 330 €/ha in both regions. Given the acute biological values of meadows the top-up is paid starting from 2006. The requirements to receive these payments are identical to the GAEC condition for DECOUP to avoid confounding results. Full details of the different policy payment schemes are given in Appendix S6. Finally, the potential effects of decoupling on world market prices were derived from the European Simulation Model (Balkhausen et al. 2008) and subsequently fed into AgriPoliS for the DECOUP and FUTURE schemes in 2005, these changes being: (i) Beef +6 %, (ii) Lamb +6 % and (iii) Cereals +4 %.

Impact analysis

We begin the results with an overview of the general effects of the three policy schemes on total agricultural policy payments, farm structure and land use, followed by the impacts on mosaic, biodiversity and ecosystem services.

Agricultural policy payments, farm structure and land use

Total simulated policy payments in 2013 are quite similar under the AGENDA and DECOUP schemes in both regions. Under the FUTURE scheme total payments fall by 51 % in Jönköping but only by 17 % in Västerbotten compared to DECOUP. In Jönköping the decline in total payments is much stronger than the decline in direct payments (i.e. 30 %) because livestock production declines and thus less coupled second pillar payments are also transferred to farmers. In Västerbotten it is the opposite; farms extend dairy production and thereby receive higher amounts of coupled second pillar payments.

Structural change is strongest under FUTURE (i.e. more farms exit and average farm size grows most) and least under DECOUP. This reflects the changes in farm income brought about by the different schemes; in particular decoupling payments increases income of small livestock farms compared to AGENDA. With decoupling these farms do not have to keep cattle to receive payments. They need only manage their land according to the minimum GAEC obligation which saves labour and other costs; consequently their incomes increase and they continue farming. As farm exit and farm growth influence the average field size and thereby the landscape, structural change has been validated in Appendix S7 where it is shown that the simulation results for each scheme are consistent with reality.

The simulated areas of the different agricultural land uses that result in 2013 from each policy scheme are shown in Fig. 3 as columns, and for comparative purposes the corresponding area in 2004 is indicated by a horizontal bar. Overall the choice of policy scheme has significant impacts on land use (and thus on landscape mosaic to be evaluated by the Shannon–Wiener Index and the average field size). The directions of the effects (increase or decrease in a particular area) are similar in both regions. They are most significant in Jönköping due to the larger changes in relative support that occur between schemes in this region. AGENDA, since it represents continuation of the status quo, results in fairly small changes in land use compared to 2004 because the attendant coupled support maintains the profitability of livestock production, particularly beef cattle. The area of arable crops however declines in both regions, though most in Jönköping (arable crops are in general not profitable in these regions and are primarily grown for rotational reasons. The declining trend in arable crops is validated in Appendix S7, Fig. S3). Due to decoupling of support from production, particularly livestock payments, DECOUP results compared to AGENDA, in a significant decline in beef production, most prominently in Jönköping. Subsequently, farmers switch a large area of arable land from intensive silage and pasture to arable grassland managed according to the minimum GAEC obligation. As a result the total areas of arable land and meadow in both regions is unaffected by decoupling.

The effects of FUTURE are qualitatively similar to those for DECOUP in that production becomes more extensive, however, due to the lower payments for maintaining the environmental quality of arable land, less land is kept in production or managed as GAEC compared to DECOUP which results in 23 % of the arable area in Jönköping being abandoned (i.e. becoming forest). In Jönköping the meadow area is also affected with 29 % being abandoned, however this is due to the indirect effects of reductions in grazing livestock in the region since the payment to meadow is similar in both DECOUP and FUTURE. In Västerbotten less than 1 % of arable land and meadow is abandoned due to the greater level of total support in this region.

Landscape mosaic

The impacts of the alternative policy schemes on landscape mosaic are evaluated in terms of the Shannon–Wiener Index and average field size. Table 2 shows the changes in these indicators resulting from each policy scheme in 2013 compared to 2004. According to this index the DECOUP and FUTURE schemes result in significant negative impacts on landscape mosaic in Jönköping (following from the changes in land use shown Fig. 3). In Västerbotten the different schemes have similar but relatively small effects. The mosaic becomes more homogenous in Jönköping under DECOUP, principally, because of the possibility to manage arable land as fallow grass (i.e. the minimum GAEC obligation)

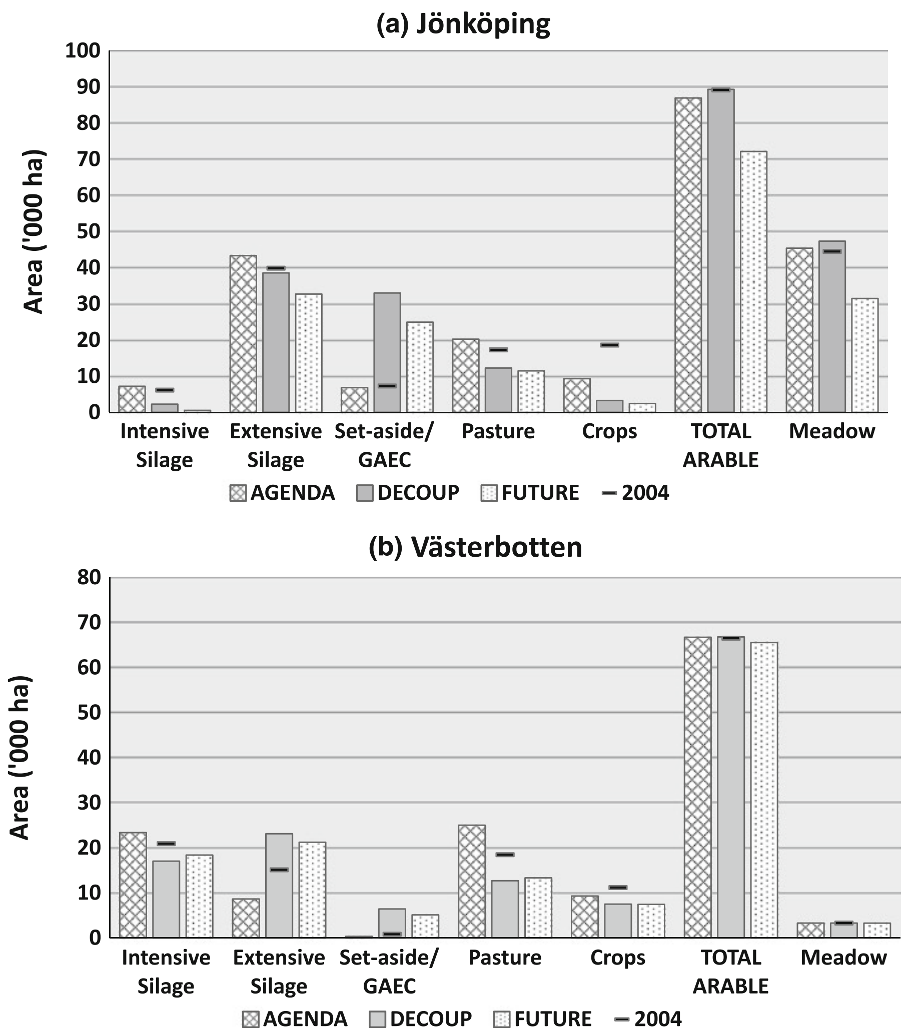

Fig. 3 Simulated land use in 2013 compared to land use in 2004 resulting from each policy scheme: **a** Jönköping County and **b** Västerbotten County

instead of having to produce crops or fodder to receive support payments. Consequently, this scheme resulted in an increase in the area of the dominating arable land use, extensive grass, compared to the situation in 2004.

In contrast the FUTURE scheme has dramatic effects on mosaic in Jönköping. Particularly the abandonment of land has a large effect as this land is assumed to regenerate to forest which is the dominating land use in the region. The strong structural change emerging from this scheme results in fewer farms managing a larger area of land and consequently, through field consolidation, the average size of fields also grows strongly (Table 2). Further, relatively small blocks that are relatively distant from farm centres are likely to have been abandoned as a part of the reduction in arable area (recall Fig. 3a) because of transportation costs which is likely to reduce connectivity.

Biodiversity

Impacts on biodiversity in terms of changes in the number of red-listed species in the two study landscapes are shown in Fig. 4 by habitat type and in total for the landscape. The total number of species (LANDSCAPE TOTAL) declined under all schemes to 2013 in both regions; the decline being least under AGENDA in Västerbotten (−1 %) and highest under FUTURE in

Table 2 Relative changes in landscape mosaic as measured by the Shannon–Wiener Index and average arable field size

	Jönköping		Västerbotten	
	Shannon–Wiener Index	Average field size (ha)	Shannon–Wiener Index	Average field size (ha)
2004	1.30	1.52	1.39	2.03
AGENDA (%)	−2	3	−2	4
DECOUP (%)	−10	3	−3	4
FUTURE (%)	−26	5	−3	5

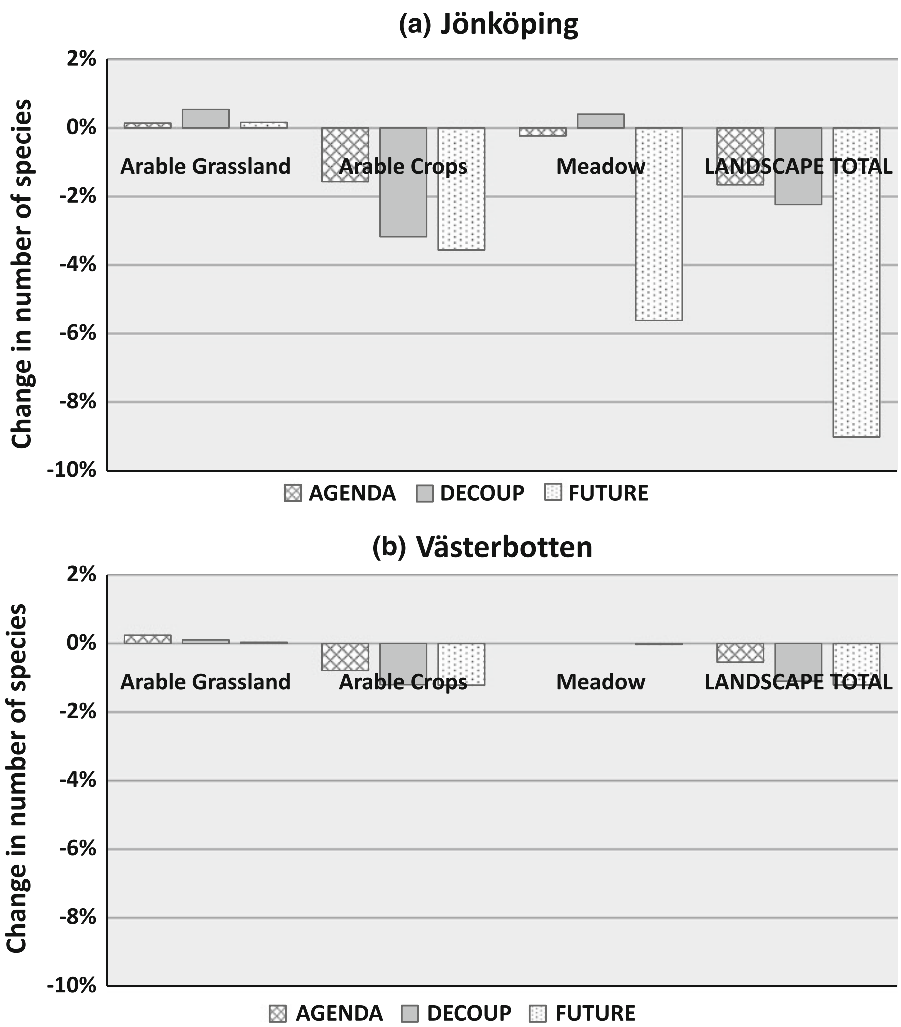

Fig. 4 Relative changes in biodiversity value by habitat type and in total resulting from each policy scheme in 2013 compared to 2004: **a** Jönköping County and **b** Västerbotten County

Jönköping (−9 %). Furthermore, the choice of policy scheme is shown to have strong effects on the distribution of species between the different habitats; the number of arable crop species is shown to decline whereas grassland species increase. Thus negative effects on species richness at the landscape scale were moderated to some extent by substitution of area between habitat types. Consequently the composition of species will also have changed in accordance with the changes in habitat area. In particular species associated with: arable crops (e.g. birds) declined significantly under all schemes but most under DECOUP and FUTURE in Jönköping; and the number of species associated with meadow declined significantly in Jönköping under FUTURE. Notably, arable grassland species increased across all scenarios and in both regions because of general reductions in the area of intensive silage (the most species poor habitat) and concurrent increases in the areas of more extensively managed grasslands (e.g. minimum GAEC). Further a reduction in species associated with arable pasture occurred under DECOUP and FUTURE (due to reductions in beef cattle numbers), but these were also compensated for by the general increases in extensive grassland area. Consequently important trade-offs are shown to occur in terms of species richness by habitat and composition at the landscape scale as a result of the choice of policy scheme.

Comparison of ecosystem services, mosaic and biodiversity

Agriculture's raison d'être is food production but it can also be important for generation of other ecosystem services. In Fig. 5 we compare changes in the value of food production (as measured by market prices), with changes in biodiversity and mosaic (Fig. 4; Table 2). For Jönköping both DECOUP and FUTURE resulted in significant reductions in food value and similar, but less severe, declines in species and mosaic value. Conversely AGENDA resulted in increased food value but also declines in species and mosaic. The results for Västerbotten are qualitatively similar to those for Jönköping except for the impact on food value that increases under FUTURE. This effect is attributable to the distortion created by the considerable national payment (€710) to dairy cows in the region. Under DECOUP it is more profitable to keep a larger area of land in more extensive uses, primarily arable grassland for beef production and GAEC (Fig. 3), whereas under FUTURE there is a strong substitution from beef to higher value milk production; hence the higher value of food under FUTURE compared to DECOUP.

In both regions the simulation results show strong correlations between declines in mosaic and biodiversity values. This is not surprising since a higher mosaic value implies a more heterogeneous landscape and consequently a greater variety of habitats to support biodiversity. The AGENDA scheme resulted in the lowest decline in habitat variety (Fig. 3) in both regions and hence in the lowest decline in biodiversity and mosaic value. However increased food production is not a guarantee for landscape values in these regions since the FUTURE scheme resulted in an increase in the value of food in Västerbotten and simultaneously a decline in biodiversity and mosaic values. Consequently the relationship between ecosystem services, mosaic and biodiversity is multifaceted and it will be necessary to optimize the trade-offs in land use to maximize the value of agricultural landscapes to society.

Discussion and conclusions

The CAP is not only a notoriously complex instrument but farming in the EU is also characterized by immense regional variation in agricultural, environmental and socio-economic conditions. Consequently, quantifying the potential impacts of CAP reform on agricultural landscapes and associated non-food values is a challenging task. In this article we presented extensions to the agent-based AgriPoliS model that create a cohesive spatial framework for simulating the potential consequences of changes in agricultural policy on farmers' land use decisions and concomitant impacts on mosaic, biodiversity and ecosystem services. The extended model provides a powerful tool for handling the complexities of CAP reform because it can capture the heterogeneity of farms and the landscape in a region, as well as modelling farm-agent behaviour and interactions in an optimization framework. The model is also empirical in the sense that the initial simulation results are calibrated with (i.e. match) observed farmer behaviour and land use patterns in a reference period. The model is relevant for studying land use change 10–25 years into the future and produces results at a relevant aggregation (county or province) for policy analysis. These things considered it represents a complement to other approaches to modelling land use change such as the scenario approach, e.g. Abildtrup et al. (2006) and Nelson et al. (2009) and agricultural sector modeling with a GIS interface, e.g. Renwick et al. (2012). For instance Renwick et al. predict that abolition of direct payments in the EU would result, on average, in

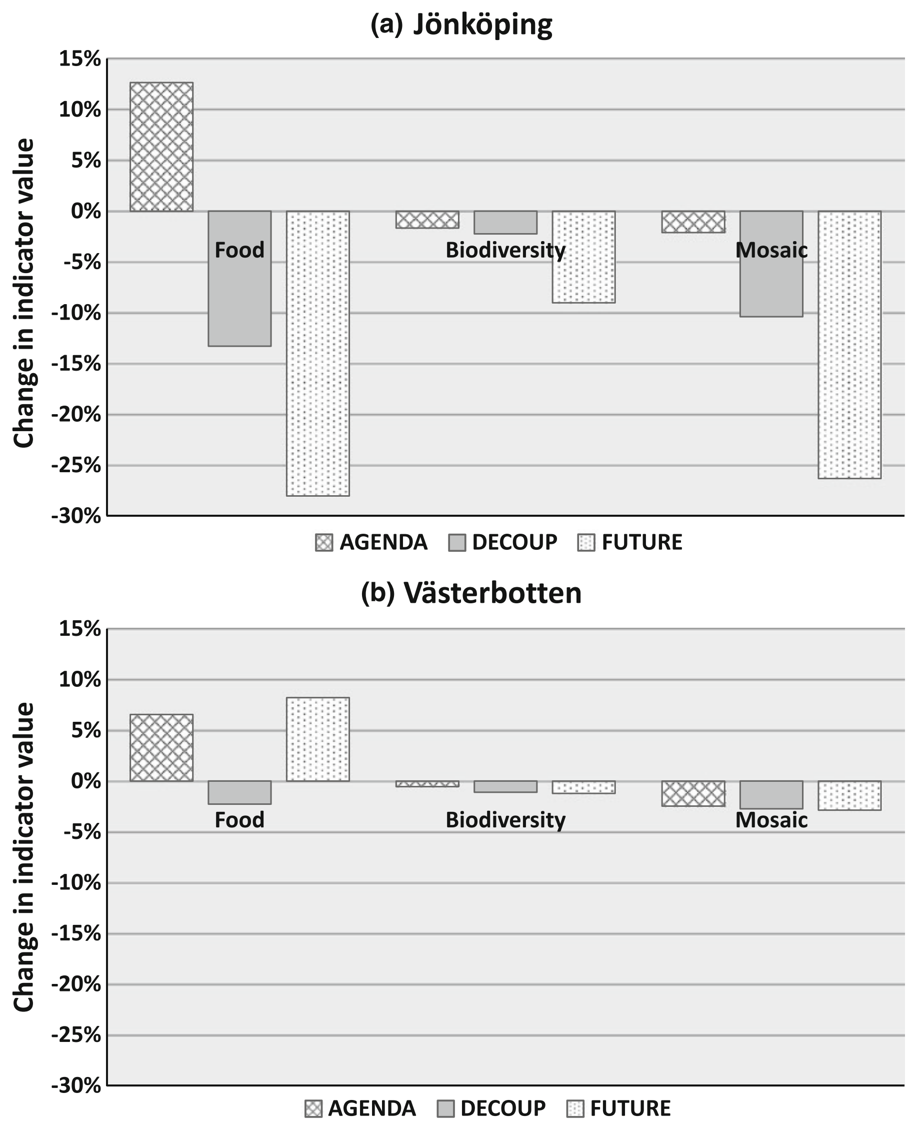

Fig. 5 Relative changes in the value of food production (€), biodiversity (nr of red-listed species) and mosaic (Shannon–Wiener Index) in 2013 compared to 2004: **a** Jönköping County and **b** Västerbotten County

7.82 % of agricultural land in the EU being abandoned, but point out that regional differences could be significant. Our results show that even a 30 % reduction in these payments would result in as much as 22 % of agricultural land being abandoned in Jönköping. The strength in our approach is being able to analyze impacts of policy reform in detail at the regional level and evaluating solutions.

We used the model to study the potential consequences of three alternative CAP frameworks or schemes—*historical* with payments coupled to production (AGENDA), *current* with decoupled payments (DECOUP) and a *future* policy where direct payments are reduced by approximately 30 % (FUTURE)—on the landscape in two typical extensive or marginal agricultural regions in the EU. Accordingly, the results do not apply to intensively farmed regions (those having high crop yields) because farmers in these regions are likely to be less reliant on policy payments and the environmental issues tend also to be of another character (e.g. pollution of water). Our results demonstrate that the choice of policy framework has significant impacts on land use and hence mosaic, biodiversity and ecosystem services in extensively farmed regions. This is because changes in the policy framework have a significant impact on the relative profitability of alternative farming activities in such regions (e.g. to choose intensive or extensive beef production) and hence induce farmers to switch between activities depending on which generates the highest returns to farmers' own labour and capital.

Further, even though we modelled two ostensibly similar regions (from a biophysical perspective) the strengths of the impacts of the alternative policy schemes were found to be very different because of the existence of other support schemes that provide farmers in Västerbotten with significantly higher total payments than those in Jönköping. Similarly existing environmental schemes also cushioned the worst potential landscape effects of the radical FUTURE scheme in Jönköping. Consequently evaluations of CAP reform need to consider interactions between the different policy payments available to farmers in any particular region, which our model is capable of doing.

Each of the analysed schemes had its advantages and disadvantages from a landscape perspective. AGENDA type coupled support ensured a greater diversity of production and hence land uses, but moreover encouraged overly intensive production to the detriment of biodiversity (which is of course a fundamental criticism of production based support to achieve landscape goals). Decoupling payments in DECOUP was effective for encouraging more extensive agriculture (a goal of the 2003 CAP reform) but to the extent that it resulted in extreme homogenization of land use, and consequently greater loss of species and mosaic value compared to AGENDA. The FUTURE scheme indicates that the potentially catastrophic impacts of eliminating income support (in extensive regions) could be greatly alleviated by strengthening agri-environmental payment schemes.

In general, significant trade-offs were shown to occur in terms of species richness by habitat and species composition at the landscape scale, as a result of the choice of policy scheme. Even the relationship between food production and other ecosystem services was shown to be multifaceted implying the need to optimize the area of different land uses/habitat and management intensity to maximize landscape value to society. In summary, our results illustrate the difficulty of achieving landscape goals in any particular region with simple or general land management rules, as they represent extremes rather than an optimal balance. This criticism applies to the minimum GAEC obligation currently operating in CAP but also to strategies like land sparing or sharing that don't consider the incentives faced by farmers (Green et al. 2005).

By linking structural change in agriculture with landscape evolution we gained the additional insight that changes in land use can have a stronger impact on biodiversity and landscape mosaic than field size growth caused by farm expansion. Therefore, preserving the existing farm size structure to avoid impacts on biodiversity and landscape is a costly approach to landscape preservation. Rather it should be ensured that agricultural land use remains diverse and that land is not abandoned. As DECOUP showed, abandonment can be avoided by linking payments to specific land management requirements. However, a minimum use of the land by simply mowing it is not sufficient; a variety of different types of land use should also be preserved.

An imperative question is just how much of the vast sums transferred to farmers in the EU each year, actually generate environmental value? Taxpayers in the EU are led to believe that their money is generating environmental stewardship (Phelps 2007) and the upcoming CAP2013 reform is marketed on environmental grounds as the "greening" of the CAP (EC 2011). Whether taxpayers are getting value for money is though a contentious issue (Kleijn et al. 2011). Our results clearly show that policy payments are important for maintaining landscapes and biodiversity in extensive regions (i.e. the DECOUP scheme) but similar levels of environmental benefit could be achieved by reducing direct payments (e.g. FUTURE). What needs to be considered is how to best go about achieving landscape management goals in the EU at least-cost to society; rather than what minimum measures need to be taken by farmers to be eligible for policy payments. Given the scarcity of funding for conservation, the answer should have major welfare economic as well as ecological implications. Clearly agricultural landscape management is a complex problem to analyze and solutions other than simple. We hope that the extended AgriPoliS model will provide a useful tool for evaluating both the economic and ecological impacts of CAP reform and hence provide decision support in a complex policy arena.

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