Scotland's Rural College

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Published in:
Agricultural Systems

DOI:
10.1016/j.agsy.2015.03.006

Print publication: 01/01/2015

Document Version
Peer reviewed version

Citation for pulished version (APA):
Guillem, EE., Murray-Rust, D., Robinson, DT., Barnes, AP., & Rounsevell, MDA. (2015). Modelling farmer decision-making to anticipate tradeoffs between provisioning ecosystem services and biodiversity. *Agricultural Systems*, *137*, 12 - 23. https://doi.org/10.1016/j.agsy.2015.03.006

Modelling farmer decision-making to anticipate tradeoffs between provisioning ecosystem services and biodiversity

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Abstract

In this paper, an agent-based model of heterogeneous farmer decision-making was coupled with an individual-based model of skylark breeding populations, and applied to a small intensive arable catchment in Scotland. The impacts of farmer decisions on a tradeoff between food and bioenergy production, and skylark numbers, were simulated under the assumptions of three socio-economic scenarios until the year 2050. Bioenergy and food production had a significant negative effect on adult and fledgling skylarks. In a business-as-usual context, the production of food and bioenergy increases smoothly, and the number of skylarks is more stable over time than in other scenarios. Food production was higher in an economic liberalisation scenario, due to intensive management and higher yield performance. This explained the low average number of skylarks found at the landscape level in this scenario. The number of skylarks was highest in a sustainability-oriented scenario, but a sharp decrease was observed from 2035 onwards due to the large area planted with bioenergy crops. The different values for economic, environmental and social attributes of farmer decisions played an important role in the land use mosaic, the implementation of ecologically-related actions and on the provision of ecosystem services and biodiversity. Overall, results suggest that a re-assessment of policy targets and design is necessary to maximise environmental management efficiency at the catchment level by taking into account the heterogeneity in farmer objectives and the tradeoffs in ecosystem services provision. The novel approach of coupling an ABM with an IBM is encouraged in further land use related studies.

Keywords: agent-based model; bioenergy crops; farmer behaviour; food production; land use change; skylark

1. Introduction

Land use and cover change (LUCC) is a major concern for the sustainability of farming areas, biodiversity levels and the provision of ecosystem services responsible for human welfare. Agricultural landscapes are largely shaped by human actions driven by socio-political and environmental stimuli (Antle et al., 2001; Lambin et al., 2001), and host a number of species that underpin the provision of ecosystem services. These species are under constant threat following changes in farming practices and management styles.

Land-related policies have been modified to prevent environmental degradation, but the reforms have created unexpected issues undetected in common *ex-ante* analysis, i.e. land abandonment and intensification of arable land use after the Fischler Reforms in 2005 (Acs et al., 2010; Holland et al., 2011; Doxa et al., 2012). In the near future, the Common Agricultural Policy (CAP) will tend towards liberalisation, which will create increasing reliance on fluctuating commodity prices and a possible switch from food to non-food production (Tranter et al., 2007), and lead to uncertain impacts on the long-term economic and ecological sustainability of farming areas (European Commission, 2010). The anticipation of consequences due to changing conditions (i.e. market, policy, climate) can be improved through the understanding of how actors within the system make decisions and when changes will occur.

Indeed, the heterogeneity of land-use activities and management observed at the landscape level has relevance in *ex-ante* analysis, but cannot be explained by common methodologies (i.e. linear programming). In the Agent-Based Modelling (ABM) approach, this landscape heterogeneity is seen from a bottom-up point of view where each actor (i.e. each farmer) is considered to react autonomously and cognitively to external pressures (e.g. Janssen et al., 2000; Berger, 2001; Murray-Rust et al., 2011). In the same way, ecological, individual-based models (IBM) can simulate species population from the behaviour and life cycles of the individuals under different LUCC scenarios (e.g. De Angelis et al., 1998; Topping et al., 2003; McLane et al., 2011).

Too often, the impacts of policy on farmer decisions and LUCC (explored via ABMs), and the effect of LUCC on biodiversity and ecosystem services (explored via IBMs) are studied separately. In general, the current ABMs and IBMs lack transparency in some of the component sub-models that drive simulation outcomes. This can be improved by integration, or coupling, of an ABM of LUCC with an IBM, which offers greater potential to understand processes and feedbacks between human and natural systems (Luus et al., 2011) and to study the indirect effect of policy on ecosystem services through farmer decision making (Milner-Gulland, 2012; Sutherland and Freckleton, 2012). Only a few studies have presented results from such a combination (Jepsen et al., 2005; Bithell and Brasington, 2009; Verburg and Overmars, 2009), but the decision maker agents were not heterogeneous, which limits the relevance of such models since not all land managers react similarly to policies (Beilin et al., 2012). Indeed, the nonlinear interactions between farmer decisions and the ecosystem, often acting at different spatio-temporal scales, cannot be considered independently since they involve feedbacks. In particular, these feedbacks occur in respect of a wide variety of ecosystem services and on species by providing or removing habitats (Antle et al., 2001; Liu et al., 2007). For instance, farmland specialist bird species (e.g. skylark, lapwing, yellowhammer), which require specific farmland habitat to nest and to feed, have decreased faster than other types of birds and drastically since the 1970s due to the intensification of agricultural land use (Siriwardena et al., 1998; Donald et al., 2002). Simultaneously, intensive agriculture allows a larger production of food, which is an important ecosystem service. Therefore tradeoffs between several services and with biodiversity levels must be considered.

This article reports on the integration of an agent-based model of farmer decision-making with an individual-based model of skylarks applied to a spatial

(Geographic Information System (GIS)) database representing a Scottish intensive arable catchment. The model represents relationships between external pressures (market, climate, and policy), heterogeneous farmer decisions about farming practices, and the effects of these on provisioning services (food production, renewable energy), and an indicator of biodiversity (skylark local population). A set of simulation experiments was carried out based on three socio-economic scenarios to test the adaptation and responses of agents to changing contexts and the effects of this on provisioning services and biodiversity.

2. Materials and Methods

2.1 Study site

The study area comprises 132 km^2 of a mostly arable catchment in the Tayside region, East Scotland (Figure 1). 115 active farmers manage the land with a mix of land use activities, essentially cereals and root crops (65%), and grasslands (35%) (Scottish Government, 2007). The study area is one of the few places in Scotland where intensive cropping occurs due to a relatively flat and fertile soil. Intensive cropping takes place on 9% of Scottish agricultural land and generates 34% of agricultural outputs (Scotland's Environment, 2014). Farmers in the catchment share similar biophysical conditions, agricultural activities and market prospects, while avoiding the problem arising from variations observed at larger scales.

This site has been intensively studied as it represents an example of a catchment with a number of typical indicators for Scottish farming and shows fragility in terms of water and air quality (Vinten et al., 2009). Since 2003, the catchment has been designated as a Nitrate Vulnerable Zone (NVZ)[1], which puts constraints on how farmers manage their land (Scottish Executive, 2003).

The catchment also includes a Site of Special Scientific Interest (SSSI) under the Nature Conservation (Scotland) Act 2004 (Rescobie and Balgavies Lochs), active fisheries, and the Balgavies Scottish Wildlife Trust reserve. In addition, the catchment forms part of the Scottish Environment Protection Agency's Monitored Priority Catchment Project, which aims to establish monitored baselines against which the effectiveness of diffuse pollution mitigation measures can be assessed (Vinten et al.,

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[1] The Environment Agency has designated conservation zones, the NVZs, to reduce the risk of nitrate polluted waters (EU Nitrate Directive 91/6/76/EEC and the EU Water Framework Directive 2000/60/EC). Restrictions include reduction of the amount of fertiliser used and limited fertiliser and animal waste application periods.

2009). Thus, the catchment and the broader region are of particular interest to policy makers.

<FIGURE 1>

2.2 Model Development

The integrated ABM/IBM comprises four components (see Figure 2):

1) An agent-based model of farmer decision-making for land uses, named "Aporia"[2] (Robinson et al., 2011; Fontaine et al., 2013; Murray-rust et al., 2014; Guillem et al., in review);
2) An individual-based model of breeding skylarks;
3) A vegetation model within which the Aporia model and the skylark IBM are coupled;
4) A sub-model that quantifies the provisioning ecosystem services (food and biofuel energy).

<FIGURE 2>

2.2.1 Agent-based model of farmer decision-making for land uses

The model represents heterogeneity in decision-making in terms of farm strategies, i.e. land use regimes per farm. A farmer agent chooses a regime, i.e. crop rotation, for each of the parcels that compose its farm, the management style associated with it (intensive or extensive) and whether an agri-environmental measure or the conversion to bioenergy crops is applied. It is assumed that these choices are based on attitudes and preference structures for the sustainability principles, i.e. economic viability, environmental quality, and social feedback (Murray-Rust et al., 2014; Guillem et al., in review).

A sample of farmers within the Lunan catchment was selected for a phone interview and the results used to obtain three attitudinal clusters of respondents: Profit-oriented (38%), Multifunctionalist (25%), and Traditionalist (36%) (Guillem et al., 2012). The proportion of each farm type was randomly allocated and associated with farm parcels within the catchment.

In Aporia a set of alternative regimes are evaluated and ranked in order for the farmer agents to select the one that maximises their utility (Murray-Rust et al., 2014). This method computes an economic (difference in gross margins), environmental

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[2] The model framework, and the software and its guidance are available freely at http://www.wiki.ed.ac.uk/display/Aporia

(land use cover, nitrogen use and diversity) and social (access to green space and tradition) attributes' score for each regime (Murray-Rust et al., 2014; Guillem et al., in review). Simultaneously, each farmer type responds to a specific aggregative nonlinear utility function in which the preferences values for these regime attributes was elicited from a choice-based conjoint survey (*ibid*).

To anticipate tradeoffs between provisioning ecosystem services and a biodiversity indicator, the change in land use in the Lunan catchment was explored in different socio-economic contexts using three hypothetical scenarios from the Assessing LArge-scale Risks for biodiversity with tested Methods (ALARM) project (Bohunovsky et al., 2011; Settele et al., 2012; Spangenberg et al., 2012): BAMBU (Business-As-Might-Be-Usual) represents the current economic and policy situation with a progressive shift of funds from the CAP pillar 1 (production) to pillar 2 (environmental enhancement); GRAS (GRowth Applied Strategy) is characterised by economic liberalism, free trade and international competitiveness - Neither direct payments nor rural development funds are proposed; SEDG (Sustainable European Development Goal) portrays environmental and social development where farmers are encouraged through financial incentives to grow bioenergy crops, to use more extensive management and to apply agri-environmental measures. The scenarios' narratives were adapted to the case study and changing factors were attributed to define market prices, subsidy levels and yield performance over time (initial values taken from SAC (2000 to 2008), and assumptions and forecasted values from Abildtrup et al., 2006)[3].

2.2.2 Skylark individual-based model

The IBM was designed to estimate the number of skylarks within the Lunan catchment emerging from individual breeding behaviour. Skylark nest suitability and number of brood per year depend mainly on vegetation structure (Chamberlain et al., 1999), which is influenced by crop type.

Behavioural rules (Figure 3*):*When entering the breeding period (from April to July), each modelled skylark male "scanned" a territory search space within the virtual GIS-based landscape, and selected a bird territory (i.e. a circular space which is suitable for a nest and a foraging area) until a maximum carrying capacity of the landscape was reached. The territories were suitable for nesting when vegetation height was comprised between 10 to 120 centimetres (Table 1). The maximum capacity was determined by multiplying the area of crops in the search space by their

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[3] A list of policy instruments and market prices used to define the scenarios is given in the supplementary materials.

specific territory density (*Ibid*). Territory densities were upgraded by 20% when a crop was extensively managed or associated with grass margins to represent less dense structure and higher availability of feeding resources for chicks (Henderson et al., 2009). If the number of territories occupied did not exceed the maximum capacity, the male set its nest in a suitable place and attracted a female. Once a male had selected a site, the site remained occupied until the male or its partner dies. In the same manner, if the vegetation structure changed and was no longer suitable, the pair sought another site or became "floaters", i.e. non-reproductive flock of birds.

When a pair established a nest, mating occurred followed by egg laying. The behavioural rules applied to the young stages, i.e. egg, nestling and fledgling, were limited to "Start" and "Die". In winter, the birds floated randomly in the catchment until a new breeding season started.

<FIGURE 3>

<TABLE 1>

Variables (Table 2): Individual skylarks were characterised by a set of dynamic variables related to their life-cycle stages and recorded daily throughout the simulations: eggs, nestlings, fledglings, adults. Mortality rates are given for each life-cycle stages from empirically-determined means with environmental fluctuations simulated using a daily modifier of 0.1% (adapted from Topping et al., 2005). The number of individual floaters was not initially set but emerged from simulations when some adults were unable to find a nest or a partner (due to the depletion of suitable territory or to the death of a mate).

<TABLE 2>

2.2.3 Vegetation model and coupling of ABM/IBM

A vegetation model (*DefaultVegetationModel)* was used to provide, for each farm parcel, a daily update of vegetation height and a yearly harvestable biomass based on crop types (for yield calculation, see Murray-Rust et al., 2014)[4]. For vegetation height, the *DefaultVegetationModel* uses different equations depending on land use. For crops, a daily growth curve was used based on empirical information collected in the Lunan catchment (own unpublished data; Figure 4). The growth was

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[4] Only the harvestable biomass increased across time due to technological improvements in each of the socio-economic scenarios. The height of vegetation is assumed to remain the same.

initiated at time of “sowing” and fell to 0 at time of “cutting”. The annual timing of these actions was crop-specific and the same each year. If a parcel was abandoned, a natural succession of shrub vegetation took place, for which the height of vegetation *H* (in centimetres) at time *t* (in day) was modelled using the Chapman-Richards equation (Equation 1).

$$H(t) = A + \frac{(K-A)}{(1+Q.e^{-B(t-M)})^{1/v}} \tag{1}$$

, with *A* and *K* respectively the lower and upper asymptote (*A=0*, *K=150*cm), *B* is the growth rate ($B=0.02\ cm.day^{-1}$), *v* is the nearest line between lower and upper asymptote (*v=0.5*), Q depends on the value at *H(0)* and *M* is the time of maximum growth when *Q=v*.

<FIGURE 4>

The vegetation model was the connecting interface by which the ABM of farmer decision-making is coupled with the skylark IBM. Indeed, the spatial resolution of both models was the parcel level, delimited by boundaries and attached to a given farmer identity. The environmental factors involved in the skylark IBM (i.e. vegetation heights and territory density) are therefore directly driven by farmers’ choices of land use managements and regimes. However, the ABM and IBM are only loosely coupled since the time-step of a changing state was asynchronous (Antle et al., 2001; Bithell and Brasington, 2009): farmer attributes and decisions, and crop yields, were updated annually while skylark behaviour, life-cycle characteristics and vegetation heights were simulated daily.

2.2.4 Food and bioenergy production

The harvesting of food for human consumption (i.e. vegetables, potatoes, cereals, beef[5]) and bioenergy crops (i.e. willow and miscanthus) was converted at each annual time-step into energy produced from the whole catchment. This was done by multiplying the amount of commodity harvested (in tonnes) by the energy value for human consumption and renewable energy using FAO and USDA conversion

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[5] We assumed that grassland biomass is used to rear beef cattle, and thus the biomass of grass was converted into tons of beef (see supplementary material for details).

coefficients (Table 3). The simulation outputs gave a cumulative sum of energy produced in the catchment.

<TABLE 3>

2.3 Initialisation and analysis of simulation results

The model was initialised with the historical spatial arrangement of land use from 2000 to 2008 using Spatially Integrated Administration and Control System (SIACS) data and run for a period of 50 years. The initial population of skylarks was estimated from the carrying capacity of the 2007 historical landscape.

Because the model included a stochastic component (i.e. mortality rates of individual skylarks), multiple simulations were performed; 10 simulations for each scenario, applied to four cases of farmer agent populations: ALL, a proportion of farmer types corresponding to the results of the social survey; Multifunctional, a population exclusively composed of multifunctionalist farmers; Profit, a population of profit-oriented farmers; and Traditional, a population of traditionalist farmers.

For the ALL simulations, a time series (2008 to 2050) of the proportion of land use types found in the Lunan catchment is given for each scenario. In addition, a time series of the cumulative sum of energy produced, averaged over the 10 multiple simulation runs, and of the average number of adult and fledgling skylarks, were compared across each scenario.

The geometric means over 10 simulations from the year 2008 onwards of adult skylarks was used to compare skylark populations in a landscape managed exclusively by a single farmer agent type. Kruskal-Wallis tests were carried out on the null hypothesis that skylark numbers were statistically similar across farmer types.

Finally, model outcomes were analysed to test the relationships between the production of food as well as bioenergy (in constant energy units, megajoules (MJ)) against the adult and fledgling population of skylarks, using a linear mixed model to account for temporal autocorrelation, i.e. 30 points, related to the 10 simulations for three scenarios, were clustered per year, giving 42 groups (i.e. the 42 groups were the 42 years of simulations) for 1260 observations. The model was computed in R using the “nlme” package (Pinheiro et al., 2009). The linear mixed model had the following form (Laird and Ware, 1982):

$$A_{i,j} = \beta_1 \cdot x_{1,i,j} + \cdots + \beta_n \cdot x_{n,i,j} + t_{i,1} \cdot z_{1,i,j} + \cdots + t_{i,p} \cdot z_{p,i,j} + \varepsilon_{i.j} \quad (2)$$

$$t_{i,k} \sim N\left(0, \psi_k^2\right), Cov\left(t_k, t_{k'}\right) = \psi_{k.k'} \quad (3)$$

$$\varepsilon_{i,j} \sim N\left(0, \theta^2 \cdot \lambda_{i,j}\right), Cov\left(\varepsilon_{i,j}, \varepsilon_{i,j'}\right) = \theta^2 \cdot \lambda_{i,j,j'} \qquad (4)$$

where $A_{i,j}$ is the resulting number of skylarks for observation *j* (*j* = 30) of cluster *i (i =42)*, $\beta_1 .. \beta_n$ are the fixed effect coefficients constant across clusters, $x_{1,i,j} .. x_{n,i,j}$ are the fixed effect regression coefficients, $t_{i,1} \cdots t_{i,p}$ are the random effect of time coefficients of cluster*i*, $z_{1,i,j} \cdots z_{p,i,j}$ are the random effects regression coefficients, $\varepsilon_{i,j}$ is the error term, $\psi_{k.k'}$ are the covariances among the random effects and are constant across clusters, $\theta^2 \cdot \lambda_{i,j,j'}$ are the covariances between errors in cluster *i*.

3. Results

3.1 Temporal effects of socio-economic scenarios on farmers' decision, provisioning services and skylark number

In BAMBU, the proportion of crop types changes noticeably at each decade (Figure 5), with an increase in root crops due to higher yielding performance, loss of set-aside and grassland[6]. The level of cereals is higher than in the other scenarios and the area planted with miscanthus remains low. The population of adult skylarks increases until a plateau is reached between 2020 and 2040, followed by a small decrease afterwards (Figure 6a). In this scenario the energy produced from miscanthus is the lowest, and does not exceed 10 terajoules (TJ), while energy from food is intermediate compared with other scenarios (Figure 6c and d).

In GRAS, the area grown under cereals is cut by 35% by 2050 compared to 2030's levels, which is replaced with root and bioenergy crops (Figure 5). Yield improvement and the resulting response from low input and output prices in GRAS allow more land to be converted to bioenergy crops without diminishing food production. Indeed, the production of food energy is the highest compared to the other scenarios, while the adult skylark population is the lowest (until around 2040).

In SEDG, the land cultivated for bioenergy crops rise from 2040 (Figure 5), leading to the highest production of bioenergy across the scenarios, which accounts for more than 50 TJ in 2050, and the lowest production of food (Figure 6c and d).The

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[6] GIS-based maps showing the simulated distribution of land-uses in the study area in two time slices, 2025 and 2050, under the assumptions of three scenarios GRAS, BAMBU, SEDG, are provided as a supplementary material.

number of adult skylarks reaches a maximum level in SEDG around 2030 while the most abrupt decrease is observed afterwards (Figure 6a). The decrease in adult and fledgling skylarks is initiated before the amount of bioenergy produced goes beyond 10 TJ and is very abrupt, as opposed to the GRAS scenario where the decrease starts later and is smoother (Figure 6a and b).

Figure 6b shows that the number of skylark fledglings produced diminishes in all scenarios over the whole period. A small increase is observed from 2020 in GRAS and SEDG when direct payments start to be reduced (drastically in GRAS and more progressively in SEDG). The only difference found in 2020 between GRAS, SEDG and BAMBU, is a greater diversity of crop types in GRAS and SEDG, i.e. presence of leguminous crops and miscanthus (Figure 5).

<FIGURE 5>

<FIGURE 6>

3.2 Effects of farmer behaviour on skylarks' number

The mean density of skylark territories over the period 2008-2050 was 0.13 per hectare and there were no significant differences between scenarios. However, Kruskal-Wallis tests were performed to test the distribution of adult skylarks across different landscapes virtually managed by each farmer type separately. The average number of skylarks over the period 2008-2050 was significantly different across the three types of landscapes (BAMBU: $p=0.007$, GRAS: $p=0.000$, SEDG: $p=0.002$) (Figure 7).

In a landscape managed exclusively by traditionalist farmers, the number of adult skylarks remains the same in the three scenarios, while there are some variations in the case of profit-oriented and multifunctionalist farmers. For profit-oriented farmers, the average number of skylarks is the highest in BAMBU, but the lowest in GRAS. For multifunctionalist farmers, the abundance is similar to the traditionalists in BAMBU and GRAS, but decreases in SEDG.

Multifunctionalist farmers generally apply environmentally-friendly practices, i.e. grass margins and spring cereals, but they also adopt newer land use such as bioenergy crops (Guillem et al., in review). This could explain the low abundance found in the SEDG scenario after 2030, in which subsidies allow bioenergy crops to be viable. The profit-oriented farmers grow cereals in BAMBU, but they manage their land more intensively and the crop mosaic is less diverse in GRAS. This type of farmer was the most proficient in adapting to rapidly changing market conditions to maximise profit. Traditionalist farmers maintained intensive regimes in all scenarios, but they use longer and more diverse crop rotations (Guillem et al., in review). In addition this type of farmer was the least likely to apply bioenergy crops. The average number of skylarks in a landscape managed by all types of farmers was very similar to those for the profit-oriented types for both BAMBU and GRAS.

<FIGURE 7>

3.3 Tradeoffs between food production, bioenergy and skylark number

The linear mixed model shows that both bioenergy and food production have a negative fixed effect on the number of skylarks and fledglings when considering potential variation due to time (random effect) (Figure 8). The fixed effect of the explanatory variables, food and bioenergy production, is the average effect over all years of the simulation. The fixed effect of biofuel production against adult and fledgling numbers is significant (respectively, t (Df=1246) = -3.785, p<0.001 and t (Df=1246) = -6.783, p<0.001), with a negative effect occurring when the production exceeds approximately 10 terajoules. Similarly, the linear relationship between food production and adult and fledgling skylark numbers is also significant (t (Df=1246) = -4.053, p<0.001 and t (Df=1246) = -3.868, p<0.001), though the fitted regression line is less abrupt than for bioenergy.

<FIGURE 8>

4. Discussion

4.1 Impacts of socio-economic contexts on farmer behaviour and skylark number

In all scenarios, an increase in skylark numbers is observed at least until 2030. This is explained by the choices most farmers make to increase the cultivation of cereals compared with the area planted in the baseline year 2008. Cereal crops have been defined as “the single most important habitat for skylarks in the UK in terms of the overall number of breeding pairs they support” (Donald and Vickery, 2000). In BAMBU, land uses are not changing as much as in GRAS and SEDG, and therefore the population of adult skylarks is relatively stable. Without subsidies, as is the case in GRAS, land uses change according to commodity price fluctuations, and the land is managed intensively. This has a negative effect on skylark numbers since, on average, these numbers are the lowest compared with the other scenarios. Economic liberalisation therefore brings uncertainty for the viability of farmland bird populations since impacts are dependent on market forces rather than on policy intervention. In SEDG, extensive regimes and grass margins, which are beneficial to skylarks, are encouraged by substantial environmental payments and one would expect an increase in the population of skylarks. However, while the number of skylarks is the highest until 2035 compared with the other scenarios, a sharp decrease was observed afterwards that can be explained by the large expansion of bioenergy cropping occurring in this scenario. Other simulation studies based on LUCC scenarios have shown the negative impact of bioenergy crops on wildlife at different spatial levels (Eggers et al., 2009; Gevers et al., 2011). In the latter study, an individual based model of skylark was used and the effect of land use scenarios was analysed. Gevers et al. (2011) found that skylark numbers were affected by the loss of crop heterogeneity when more than 13% of the land was replaced with maize, but it was also largely explained by the loss of set-aside replaced with these crops. In this study, static land use scenarios were used that did not simulate explicitly any possible lag effect that might occur in real world situations (Liu et al., 2007). We found that the negative effect of bioenergy production on skylark abundance occurred at different times in SEDG and GRAS. Two conclusions can be drawn from this observation. First, since the same area grown with miscanthus produces less energy in SEDG than in GRAS, due to the difference in yield performance, the amount of bioenergy becomes a poor indicator for assessing the impact on skylarks under a given renewable energy target as opposed to an area. Second, the low production of food energy in SEDG could also increase risks for the skylark population, despite the negative relationship described in Section 3.3. This indicates that a possible minimum threshold of food production as well as a maximum proportion of land converted to bioenergy crops are required to sustain skylark populations.

The overall decrease in fledgling numbers could be an effect of the population equilibrium state; e.g. when the number of adults increases, less fledglings are produced. However, from 2040 onwards both the number of adults and fledglings decreases. Likewise, it has been found that as the territory density of the overall landscape increases, with a large area being planted with cereals, the size of territory shrinks resulting in lower reproductive success (Both and Visser, 2003). This trend implies the presence of an ecological trap, which often leads to population extinction (Battin, 2004), possibly explaining why the number of skylarks decreases after 2040 in all scenarios. However, in this model, the environment has closed boundaries, which does not allow the population to diffuse to surrounding landscapes. This leads to individual skylarks using the landscape to its maximum carrying capacity, establishing nests in sub-optimal conditions (e.g. use of habitat with minimum and maximum vegetation height). Secondly, food availability to skylark was not explicitly modelled and this could have resulted in an overestimation of the number of skylarks, especially in the economic liberalisation scenario, where intensive management reduce significantly the presence of invertebrates for young skylarks (Topping et al., 2005).

4.2 Importance of farmer heterogeneous decision-making on ecosystem services and biodiversity delivery

The crop mosaic, intensity pressures and provision of ecosystem services in a landscape arise from the decisions of individual farmers. The proportion of farmer behavioural types in the Lunan catchment had an effect on the provision of food and bioenergy, and on skylark abundance. There was however a dominant effect of the way profit-oriented farmers manage their farms in both BAMBU and GRAS, neutralising the positive environmental outcomes expected from other farmer types. The profit-oriented farmers are the most represented in the population of farmers (38%) and they favour the economic viability of the business over the enhancement of habitats for farmland birds (Guillem et al., 2012; Guillem and Barnes, 2013). In SEDG, the aggregate effect of heterogeneous farmer decision-making leads to higher skylark abundance than would be expected in simulations with exclusive farm types. This is possibly a result of the combination of high uptake of agri-environmental measures and extensive regimes up to 2025, and of a variety of farming objectives, which have a cumulative beneficial effect on skylarks; as opposed to BAMBU and GRAS where production and intensification dominate. In Guillem et al. (in review), the consequences of the SEDG scenario on LUCC and management styles were greatly influenced by farmers' environmental and social values. Therefore, farmer (positive) values for the environment, when they are encouraged appropriately, are important to ensure skylark abundance and probably other ecologically-related aspects of the landscape.

Nevertheless, a positive attitude towards birds and socio-environmental objectives do not always benefit skylarks. For instance, bioenergy crops, which scored the highest for the environmental attribute in the model (i.e. do not require large amounts of nitrogen and provide a winter cover against soil erosion (see Guillem et al., in review)), were applied by the multifunctionalist farmers to a large area because they wish to maximise environmental benefits over the farm, but had a deleterious effect on skylarks. This highlights the importance of appropriate information on the ecological risks associated with bioenergy cropping, which are advertised as environmentally-friendly.

4.3 Negative effect of food and bioenergy production on skylarks

The study revealed a negative effect of bioenergy and food production on adult and fledgling skylarks. In mid-May, during the middle of the breeding period, the height of miscanthus is no longer suitable and the birds have to seek other territories (see Figure 4). It is possible that, at this period, most of the adjacent fields are already occupied leading these birds to become non-reproductive floaters. This was verified by the more severe decrease in fledgling numbers when the production of bioenergy increases, meaning that the breeding period is shortened and less breeding attempts will occur. However, previous field studies related to bird and bioenergy crops showed that miscanthus supports a higher density of breeding skylarks than other arable crops, but at an early stage of crop establishment when the vegetation does not exceed a maximum threshold (Semere and Slater, 2007; Bellamy et al., 2009; Sage et al., 2010). The high skylark density found in the literature was explained by a significant proportion of bare ground and the presence of weeds on which adults feed. Hence, if bioenergy cropping becomes increasingly viable, there is a risk that improved technology aiming at maximising yields will lead to the loss of these benefits. Since high density of skylarks only occurs at the beginning of the breeding season in miscanthus, it is also evident that a certain degree of crop diversity should be maintained for the birds to continue breeding in adjacent fields (Chaney et al., 1997).

The provision of food is also shown to have a negative impact on skylarks. In contrast to bioenergy, this relationship is not a function of the area planted with food crops. A large area planted with food crops is in fact advantageous for skylarks, but the intensity at which these crops are managed has more impacts. Donald et al. (2002) found a negative relationship between yield improvement and population trends of farmland bird. This is difficult to measure in ecology-based studies since food crops are very diverse and offer a variety of habitats. Nevertheless, it is particularly relevant to test the effect of policy targets, in particular food security, by quantifying both the level of food and energy required at the European and regional levels, and the variations this induces in the abundance of birds. With further intensification and an increase in yield performance due to technology and climate change, the risk increases for the viability of skylark populations.

4.4 Reflection on the approach

The coupled ABM/IBM allowed the study of provisioning ecosystem services and of skylark numbers at landscape level that emerge from farmers' individual valuation of sustainability. This means that qualitative and quantitative case-specific information on various “agents” or “individuals” that act at different spatio-temporal and organisational scales can be linked within a single dynamic process. Hence, the ability of an ABM to simulate LUCC is extended to new functionalities such as the simulation of changes in ecosystem services and biodiversity levels. This is of great importance to, on one hand, quantify dynamically the human decisions’ outcomes (provision of ecosystem services and biodiversity), and thus anticipate the impacts of changing and uncertain circumstances. On the other hand, tradeoffs between different ecosystem services and biodiversity levels can be assessed, which will allow efficient policy making (An et al., 2014).

This approach simulates empirically the so-called “Coupled Human-Nature Systems” (CHANS) with its complexity (An et al., 2014), i.e. heterogeneity (of farmer behaviour), emergence (from individual farmers and skylarks), non-linearity (e.g. utility function) and feedbacks (e.g. farmers’ adaptation and learning from the impacts of their practices on biodiversity, see Figure 2). In the coupled model presented here, the feedback processes are not yet implemented but are of high interest to policy makers, especially for the development of instruments such as payment-by-results agri-environmental supports, and adaptive co-management (Goldman et al., 2007; Schwarz et al., 2008; Polasky et al., 2011). Indeed, in this version of the model, farmers chose regimes as a function of their economic, environmental and social values that are computed using a simple scoring system (see Guillem et al., in review). However, the scores are static over time and do not consider bi-directional feedbacks (see Figure 2) that could emerge from the skylark IBM and impel farmer agents to re-consider their choices. For example, the uptake and outcomes of per-clutch payments (Verhulst et al., 2007) or sward height measures (SNH, 2005) could be explored, but would necessitate the estimation of the utility of an attribute of decisions specific to bird impacts.

The model presented here has some limitations in terms of predictability and concept. If the model were fully predictive, the ABM/IBM coupling could be used to answer specific questions about assigning proportions and combinations of land uses to enhance ecosystem services and biodiversity. The issue with coupling the ABM of farmer decision-making with the IBM of skylarks was the spatial scale. Farmers are indeed easily contained within a virtual catchment as they interact essentially within their household and farm parcels. For skylarks this is unlikely, i.e. there is a spatial diffusion to areas outside the case study, and assumptions must be made at this point.

Some other aspects in the ABM must be improved (see Murray-Rust et al., 2014). The difference in crop height should be related with the improvement of technology stipulated in the socio-economic scenarios. In the same manner, a gross to net factor has to be applied for the calculation of gross margins. Indeed, we can expect a difference in tax level across time and scenarios.

The aggregate, or emergent, effect of heterogeneous farmer decisions was assessed on a small number of ecosystem services, essentially the provisioning (food and bioenergy) and on a unique indicator of biodiversity (skylarks). We have demonstrated the negative relationship between bioenergy and food production on skylark number, but one can ask what would be the impacts on other ecosystem services or biodiversity indicators. For instance, while cereal cropping maximises the production of food and the availability of nesting habitat for skylark, it does not induce a high level of carbon storage (compared with grassland) or the accessibility to recreational assets (see additional examples in Bennett et al., 2009; Power, 2010; Setälä et al., 2014). The Aporia framework implements additional ecosystem services assessors such as landscape aesthetics, carbon storage and nitrogen cycle (Murray-Rust et al., 2014), but these have not been applied to the Lunan catchment yet.

In parallel and adversely to the requirements for increased level of complexity enumerated above, generalisation could also be addressed in future development. The tradeoffs between ecosystem services are global issues (e.g. the necessity to provide food to developing countries and escalating population while maintaining a sustainable environmental level) and policies are usually designed at large scale (regional, national, continental). This alternative approach to the model development will however imply the loss of details in data and require modification in model concept.

5. Conclusion

Through the coupling of an ABM of farmer decision-making with an IBM of skylarks, we have shown that the viability of the local population of skylarks and the provision of food and bioenergy are intrinsically related to the landscape level arrangement of crop types and management styles. Simultaneously, it is individual farmers with differing values for the sustainability principles that decide on crop types and management styles. Economic liberalisation is not a good option for sustaining farmland birds since it encourages most farmers to produce intensively in accordance with market signals and to abandon agri-environmental measures. Farmers who have environmental objectives play an important role in the preservation of farmland birds, but this requires substantial reward, especially if other policy goals have to be met (food security and bioenergy target). For that reason, single ecosystem services should not be assessed and targeted in isolation, and careful information should be passed to farmers on the possible tradeoffs that exist between services and biodiversity indicators. The formulation of policies should strategically take account of tradeoffs between ecosystem service and biodiversity indicators, as proposed by Haughton et al. (2009) and by the European Environmental Agency (EEA, 2007), but in a dynamic manner, and should, we argue, also include farmer heterogeneity in decision-making. This could be achieved through collaborative plans at the scale of several farm units. Each decision maker within this spatial scale would have different functions depending on their interests, skills and other objectives. An alternative implies the collaboration of farmers with similar goals to achieve targets that are realizable at larger scales than the farm and in a complementary manner (Pelosi et al., 2010).

The novel approach presented here has proven effective in the advancement of simulation models of land use dynamics and policy-making. Improvements of this method as well as applications to other case studies are worthwhile for further research.

Acknowledgements

This research was funded by the Rural and Environment Research and Analysis Directorate (RERAD) of the Scottish Government. The authors would also like to thank the RSPB Scotland, in particular Professor Jeremy Wilson for his help on skylark ecology.

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List of Figure captions

Figure 1 - Location of the case study, the Lunan catchment, in Scotland, and farm (shaded colours) and parcels boundaries within the catchment (SIACS, 2007). (1590 parcels, min=0.03 Ha, max=85.86 Ha)

Figure 2 – Conceptual framework of the coupled ABM/IBM. The dotted lines represent feedbacks that are not implemented in the current version of the model.

Figure 3 – Behavioural rules applied to individual adult skylarks. The rules of If-Then type are in grey (Y: yes, N: no). The “Die” rule is not linked with another behaviour but with life-cycle stages.

Figure 4 – Crop vegetation curves derived from survey data. The darker grey represents the suitable vegetation height for skylark nest establishment (10-120 cm).

Figure 5 - Relationship between number of adult skylarks and a: Bioenergy produced, b: Food energy produced; and between number of fledglings produced and c: Bioenergy (MJ), d: Food energy (MJ).

Figure 6 - Ecosystem services for the three ALARM scenarios, a: Average number of adult skylarks (age>300 days), b: Average number of fledglings produced, c: Bioenergy (MJ), d: Food energy (MJ).

Figure 7 – Proportion of land cultivated by the different land use types considered in the model under the three scenarios, B: BAMBU, G: GRAS, S: SEDG.

Figure 8 - Average number of adult skylarks over the 2008-2050 simulation period in a landscape managed exclusively by multifunctionalist (MULTIFUNCTIONAL), profit-oriented (PROFIT), traditionalist (TRADITIONAL) farmers, and in the landscape managed by the actual population of farmers (ALL).

List of tables

Table 1 – Parameters and values for the suitability of nest sites. *T* is the maximum territory density per hectare

Table 2 – Parameters and values of life cycle traits in skylarks used in the model

Table 3 – Energy conversion from food and bioenergy products

Table 1 – Parameters and values for the suitability of nest sites. *T* is the maximum number of territories per hectare

Parameters	Value	References
Vegetation height	Min=10cm; Max=120cm	Own field survey[a]
$T_{WinterWheat}$	0.141	Own field survey[a]
$T_{SpringCereal}$	0.135	Own field survey[a]
$T_{WinterBarley,Oat}$	0.077	Own field survey[a]
$T_{OilseedRape}$	0.062	Own field survey[a]
$T_{RootCrops}$	0.091	Own field survey[a]
$T_{Legumes}$	0.173	Own field survey[a]
$T_{GrassMowing}$	0.072	Own field survey[a]
$T_{IntensiveGrazing}$	0.084	Browne et al., 2000
$T_{ExtensiveGrazing}$	0.101	Browne et al., 2000
$T_{RoughGrazing}$	0.059	Browne et al., 2000
$T_{Miscanthus}$	0.030	Sage et al., 2010
T_{Willow}	0.095	Sage et al., 2010
$T_{SetAside}$	0.360	Browne et al., 2000

[a] Field survey carried out in the Lunan catchment in 2009; unpublished data.

Table 2 – Parameters and values of life cycle traits in skylarks used in the model

Parameters	Value	References
Age of maturity (days)	300	Delius, 1965
Territory search space	ø 500m	maximum territory size ø 250m, Odderskaer et al., 1997
Number of eggs laid	4	Delius, 1965; Robinson, 2005
Daily probability of egg mortality[a]	0.0293 ±0.1%	Chamberlain and Crick, 1999
Daily probability of nestling mortality[a]	0.0536 ±0.1%	Chamberlain and Crick, 1999
Daily probability of fledgling mortality[a]	0.027 ±0.1%	Poulsen et al., 1998
Daily probability of adult mortality (breeding season)[a]	0.00197 ±0.1%	Wolfender and Peach, 2001
Daily probability of adult mortality (winter)[a]	0.00275 ±0.1%	Topping et al., 2005
Lifespan (days)	max 3285	Staav and Fransson, 2008
Sex ratio	1:1	Dougall, 1997
Mating to egg laying (days)	5	Wilson et al., 1997
Egg laying interval (days)	1	Delius, 1965
Incubation (days)	11	Wilson et al., 1997
Caring for young (days)	19	Delius, 1965

[a] These values are transformed from yearly rate (S) to daily rate (d) using the following equation: $d = 1-(S^{(1/n)})$, with n the length of a given lifecycle stage (days).

Table 3 – Energy conversion from food and bioenergy products

	Energy (MJ/ton)	Reference
Wheat	13975	FAO[b]
Barley	13891	FAO[b]
Oat	16108	FAO[b]
OSR	20669	FAO[b]
Potatoes	32217	USDA[c]
Turnips	15062	USDA[c]
Carrots	30125	USDA[c]
Peas	33890	USDA[c]
Beans	28033	USDA[c]
Willow[a]	17200	Valentine et al., 2008
Miscanthus	17000	Natural England[d]
Beef	6070	USDA[e]

[a] net energetic value of wood at 35% moisture. value in MJ/oven dried ton

[b] http://www.fao.org/economic/ess/ess-data/ess-fs/ess-nutritive/en/

[c] http://www.ars.usda.gov/SP2UserFiles/Place/12354500/Data/SR23/reports/sr23fg11.pdf

[d] http://www.naturalengland.org.uk/Images/miscanthus-guide_tcm6-4263.pdf

[e] http://nutritiondata.self.com/facts/beef-products/3477/2

Figure 1 - Location of the case study, the Lunan, in Scotland, and farm (shaded colours) and parcels boundaries within the catchment (SIACS, 2007). (1590 parcels, min=0.03 Ha, max=85.86 Ha)

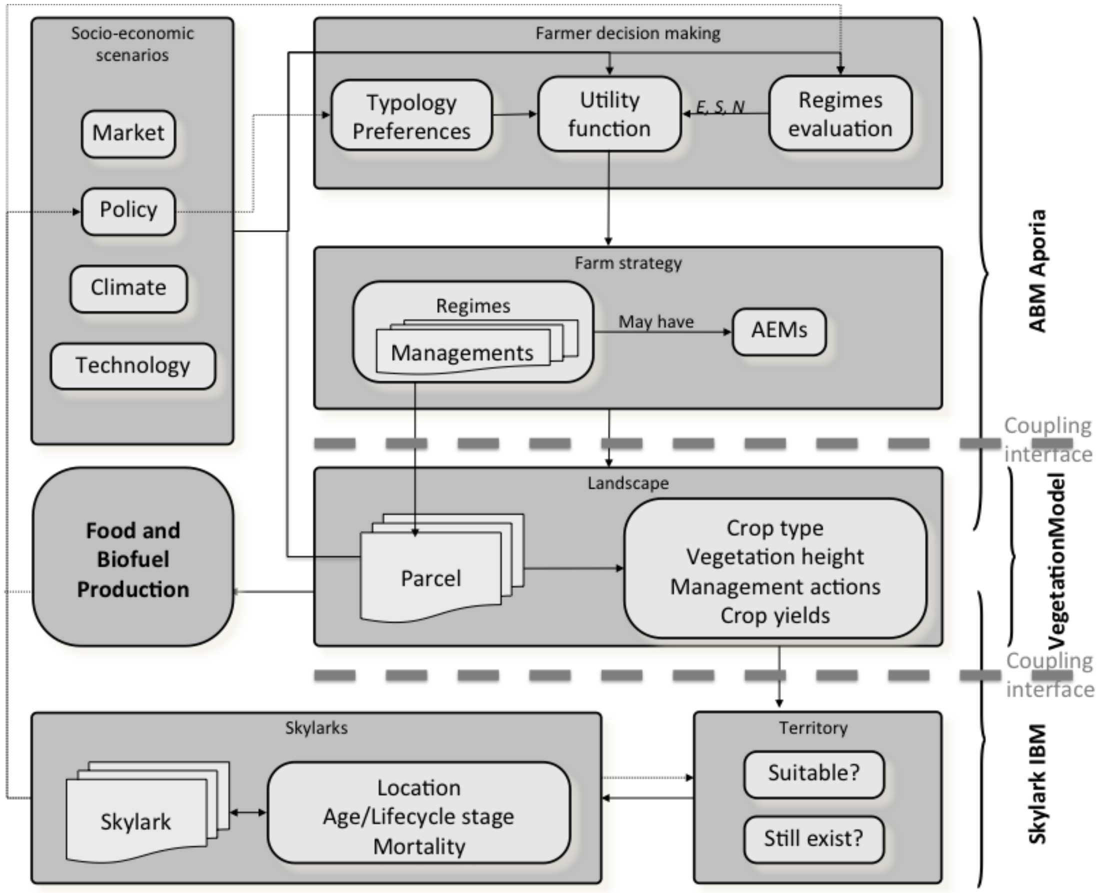

Figure 2 – Conceptual framework of the coupled ABM/IBM. The dotted lines represent feedbacks that are not implemented in the current version of the model.

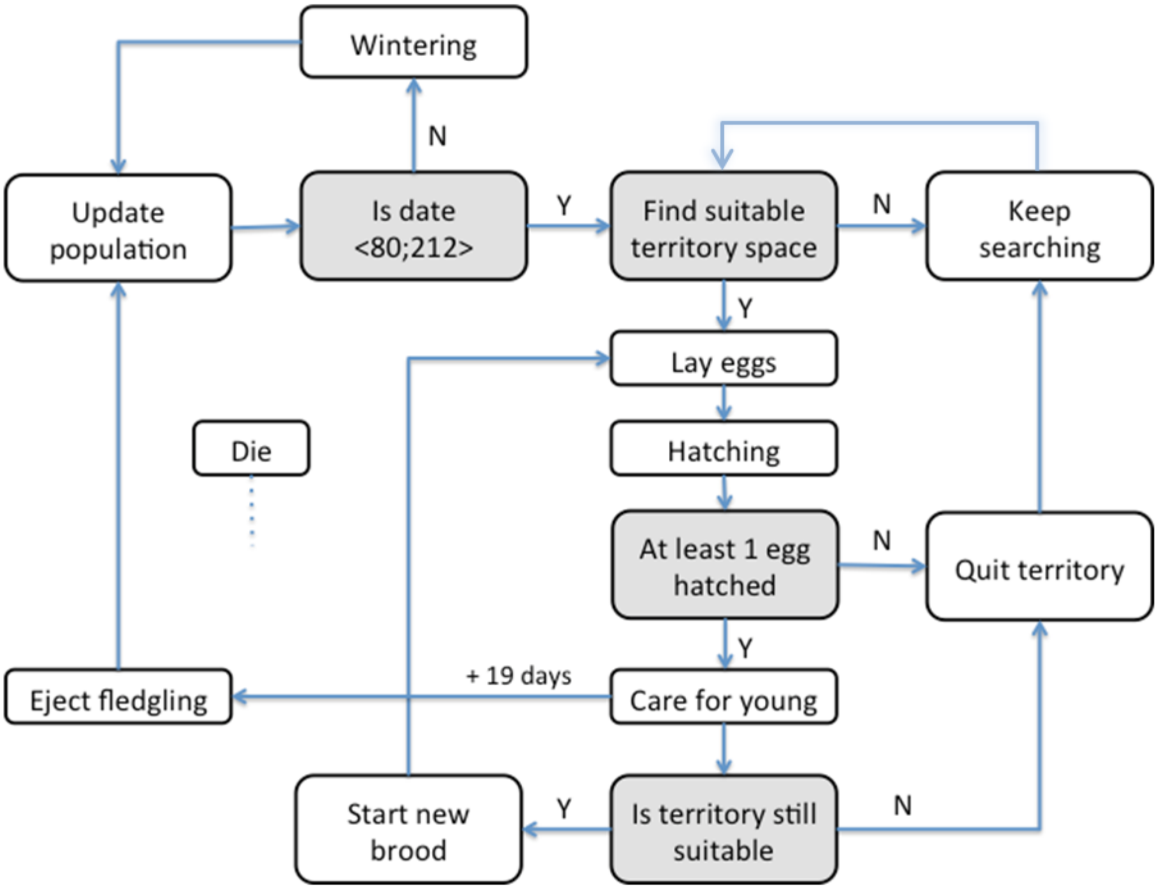

Figure 3 – Behavioural rules applied to individual adult skylarks. The rules of If-Then type are in grey (Y: yes, N: no). The "Die" rule is not linked with another behaviour but with life-cycle stages.

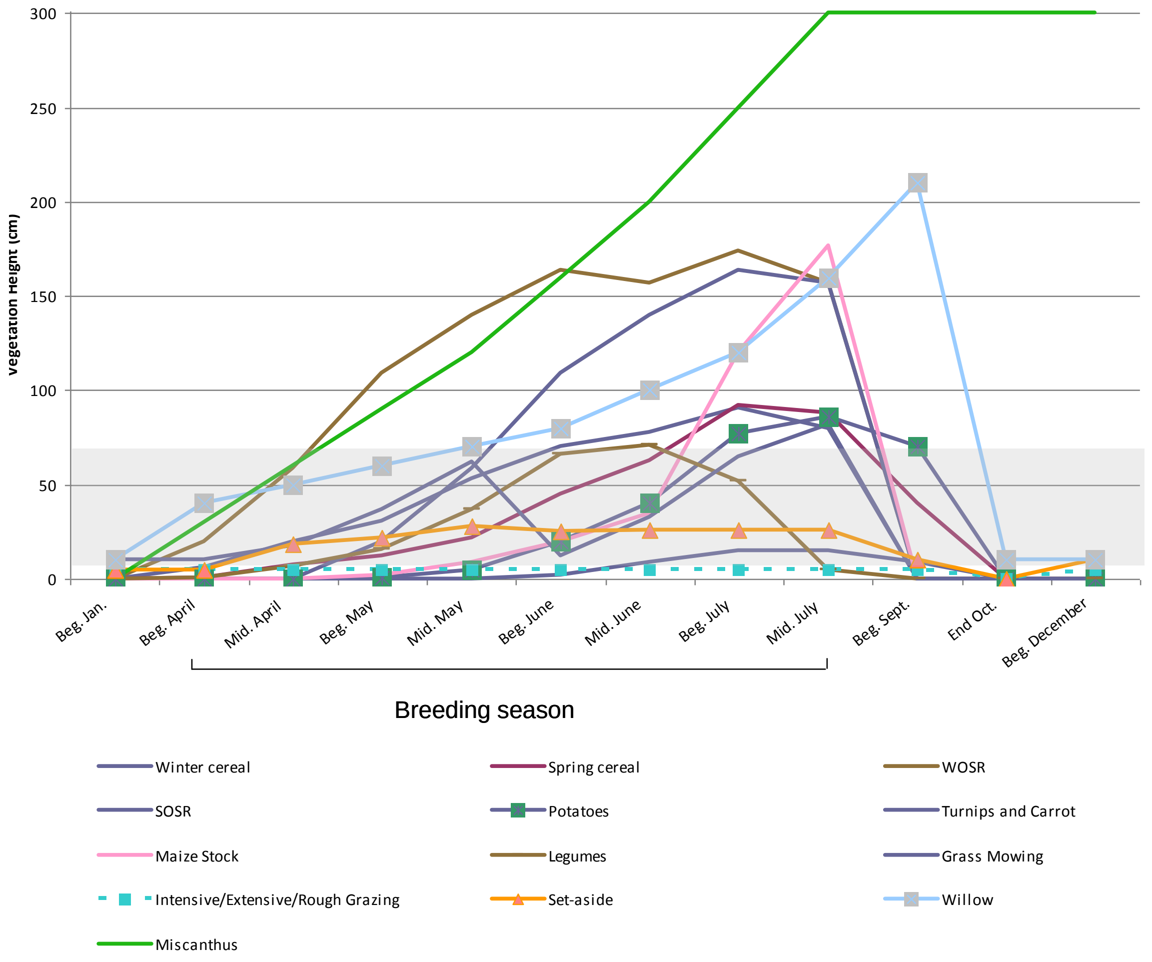

Figure 4 – Crop vegetation curves derived from survey data. The darker grey represents the suitable vegetation height for skylark nest establishment (10-120 cm)

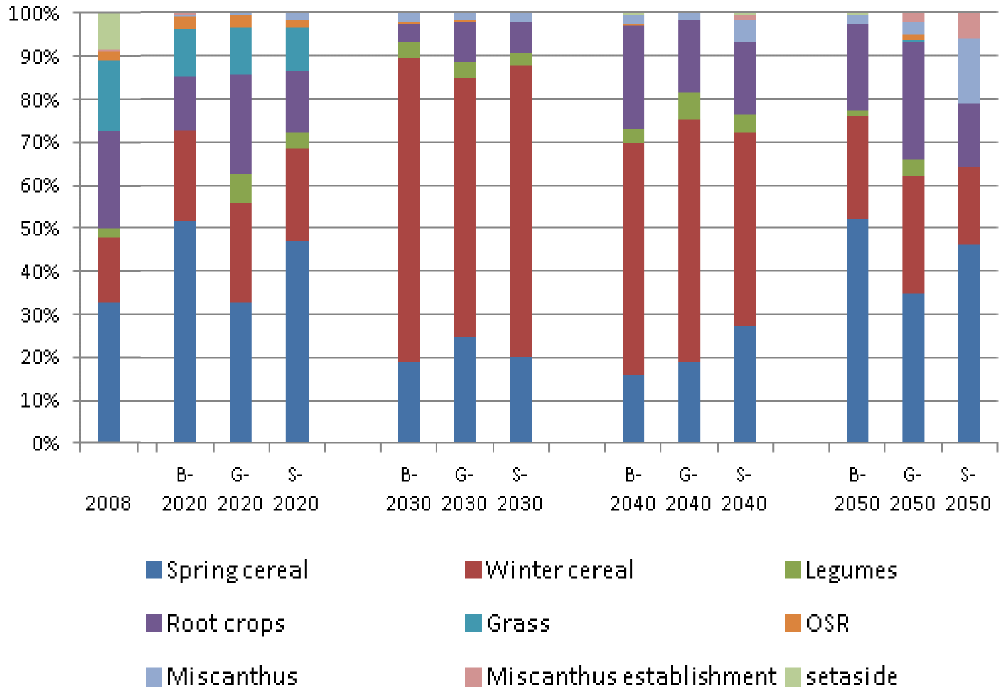

Figure 5 – Proportion of land cultivated by the different land use types considered in the model under the three scenarios, B: BAMBU, G: GRAS, S: SEDG

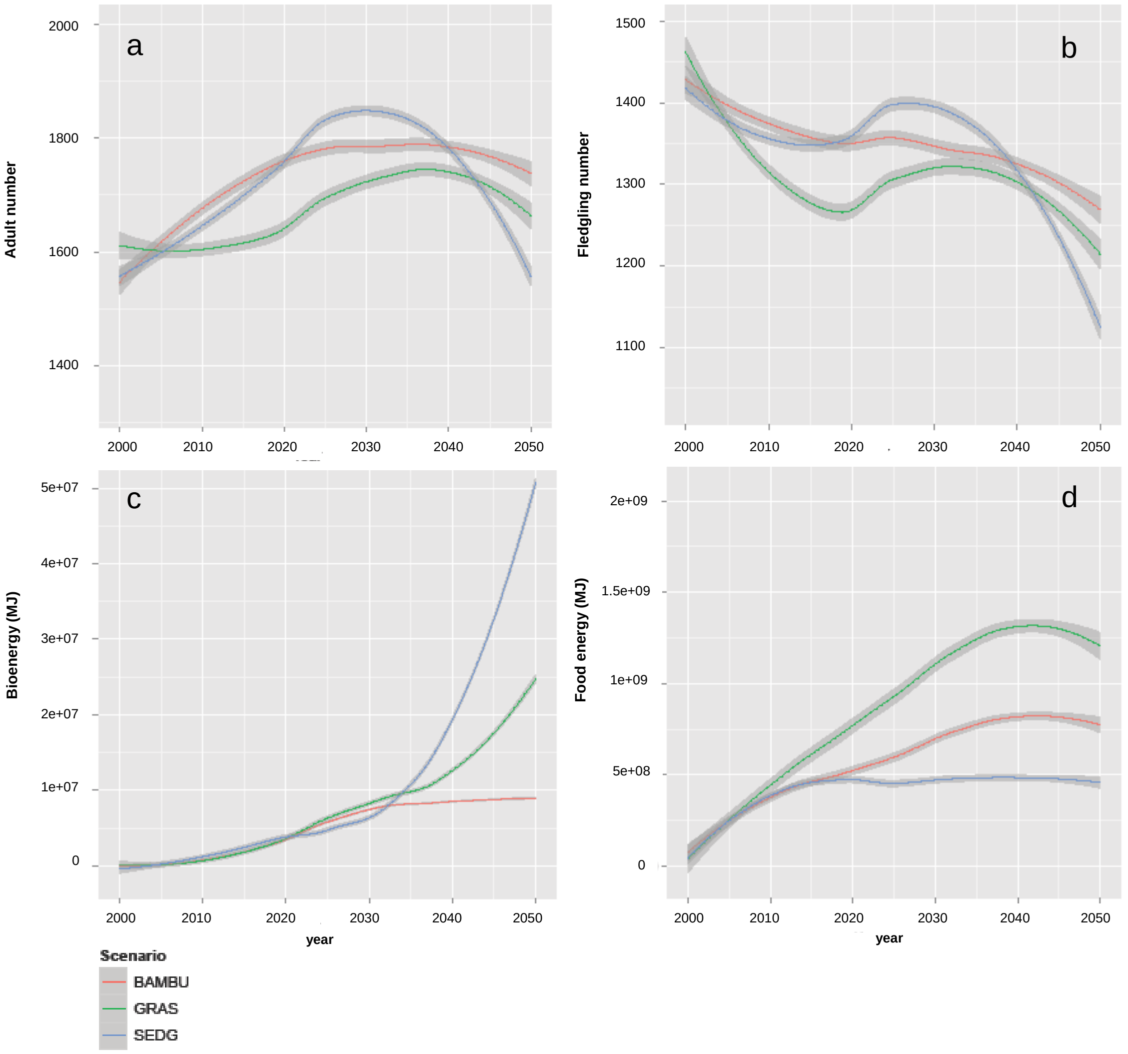

Figure 6 - Ecosystem services for the three ALARM scenarios, a: Average number of adult skylarks (age>300 days), b: Average number of fledglings produced, c: Bioenergy (MJ), d: Food energy (MJ)

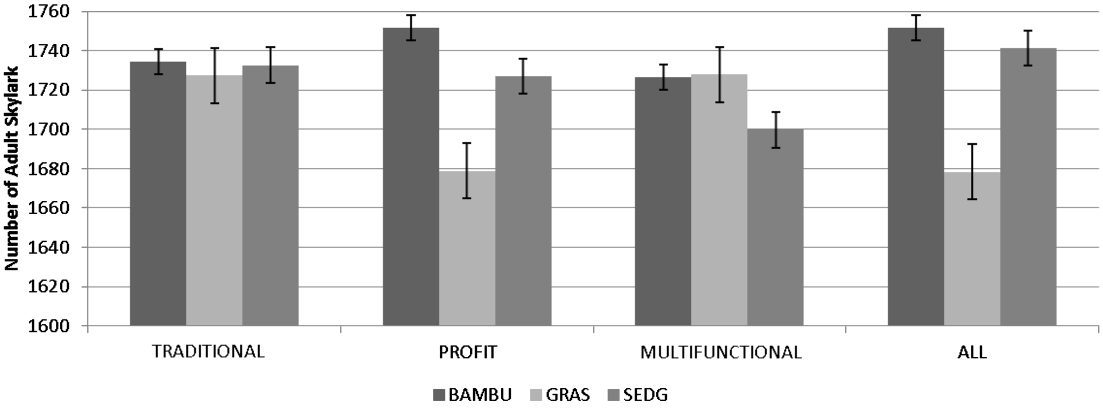

Figure 7 - Average number of adult skylarks over the 2008-2050 simulation period in a landscape managed exclusively by traditionalist (TRADITIONAL), profit-oriented (PROFIT), multifunctionalist (MULTIFUNCTIONAL) farmers, and in the landscape managed by the actual population of farmers (ALL)

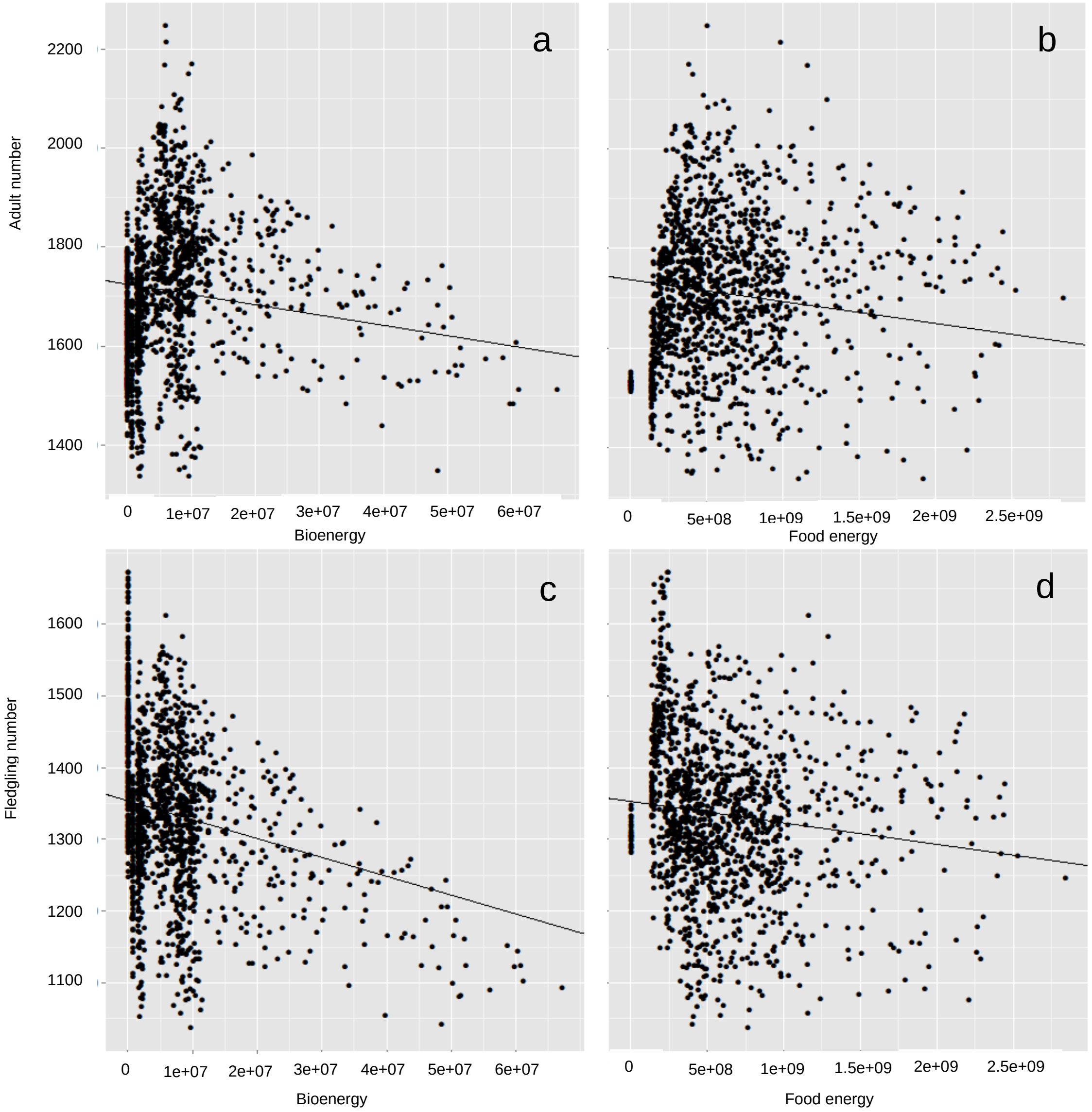

Figure 8 - Relationship between number of adult skylarks and a: Bioenergy produced, b: Food energy produced; and between number of fledglings produced and c: Bioenergy (MJ), d: Food energy (MJ)