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# Conceptualising the analysis of socio-ecological systems through ecosystem services and agent-based modelling

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In this article we present a conceptual model for analysing socio-economic systems using agent-based modelling, with ecosystem services as the focus of analysis. This is designed to allow the development of integrated models of human land managers, the landscapes which they manage and certain species of interest which live in these landscapes. We argue that in order to understand the effect of humans on the landscape and ES provision, we must take into account the preferences and priorities which they have; it is necessary to firmly embed their models into a rich socio-ecological model context, while taking into account the idiosyncrasies of human decision making. This requires a rich representation of plant and animal responses to human actions, in order to provide dynamic feedback on the results of courses of action and move beyond the static indicator frameworks commonly used. After exploring possible implementations of parts of the conceptual model, we conclude that it will provide a useful tool for analysing the effects of human behaviour on ecosystem services.

**Keywords:** agent-based model; LUCC; human–environment interactions; coupled human-environmental system; socio-ecological systems

## 1. Introduction

Understanding the complex, dynamic and non-linear relationships between humans and the environment remains a complex problem (MEA 2005). It is not enough to consider the effects of humans on their environment; we must consider the *socio-ecological systems*[1] (SES) (Gallopín 1991; Gallopín, Funtowicz, Oconnor, and Ravetz 2001), which include human and biophysical subsystems in mutual interaction (Gallopín 2006; Luck *et al.* 2009; de Chazal and Rounsevell 2009). There are a number of studies which indicate that the creation of integrated models is essential to understanding these complex SES (e.g. Carpenter, Brock, and Hanson 1999; Matthews and Selman 2006; Young *et al.* 2006).

Nature provides human society with a vast diversity of benefits such as food, fibres, clean water, healthy soil and carbon capture and many more. Our well-being depends entirely on the continuous flow of these ecosystem services (ES). The millennium

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ecosystem assessment (MEA 2005) grouped ES into four broad categories: *provisioning, regulating, supporting* and *cultural*. The loss of ES and biodiversity is an environmental and developmental problem, which results from complex interactions between natural and socio-economic causes among which climate and land use/cover change (LUCC) are paramount. In particular, LUCC has been widely identified as a human-induced factor that has a dramatic impact on ecosystem structure and processes and hence on the services they provide (Turner *et al.* 1997; Lambin *et al.* 2001; MEA 2005). Other authors further insist that LUCC affects all types of ES (Foley *et al.* 2005; Metzger, Rounsevell, Acosta-Michlik, Leemans, and Schroter 2006; Quetier, Lavorel, Thuiller, and Davies 2007; Schroter *et al.* 2005). Traditionally, the impact of LUCC has been explored for individual ES, ignoring potential trade-offs between the provision of different services. Arguably, this lack of a holistic approach is precisely why maximising specific ES such as food production in Europe has had such a detrimental impact on the environment.

The Drivers–Pressures–States–Impacts–Responses framework (Holten-Andersen, Paalby, Christensen, Wier, and Andersen 1995) has evolved into an interdisciplinary tool for environmental analyses (EEA 1995, 1999). The framework is useful in that it provides a structure in which a number of physical, biological, chemical and societal indicators can be analysed to set and evaluate targets and give a clear picture of progress or lack of progress in a number of policy areas (EEA 1999). One concern about the DPSIR is ambiguities in the delineation of components; this can be resolved by creating domain-specific specialisations – for example, the Framework for Ecosystem Service Provision (FESP) (Rounsevell, Dawson, and Harrison 2009) applies this to ES. A second criticism is that the DPSIR is a static system, which does not model system dynamics and assumes a linearity of cause and effect (Rekolainen, Kamari, Hiltunen, and Saloranta 2003; Svarstad, Petersen, Rothman, Siepel, and Watzold 2008). However, this can be seen as arising from confusion over whether it is a model or an analysis framework (Rounsevell *et al.* 2009), and indicates that the sub-components of the analysis framework should be *operationalised* through the use of models, which can address the processes and feedbacks of the SES that they are analysing (Carpenter *et al.* 2009).

When considered from the point of view of land managers, ES must be seen not as the sole focus of their thinking, but as one factor in a complex web of goals and outcomes that must be constantly balanced. Agent-based modelling (ABM) provides a tool for modelling this kind of complex decision making in land use and ecological modelling (Parker, Manson, Janssen, Hoffmann, and Deadman 2003; Bousquet and Page 2004; Matthews, Gilbert, Roach, Polhill, and Gotts 2007; Clifford 2008).

Taken together, this suggests the need for an integrative, multi-ecosystem approach to modelling SES, using ES as an output and using ABM to model the actions of humans on ecosystems.

In this article, we begin by defining certain key points of a model that uses ABM to model SES, using ES as an output, and discuss how the components of the model can be reified. We then give examples exploring how some components of the model can be implemented, with particular reference to representing human behaviour in an ABM.

## 2. Principles of the conceptual model

By taking ES as the focus of an investigation of SES, the key features of the system can be split into three interacting sub-models;

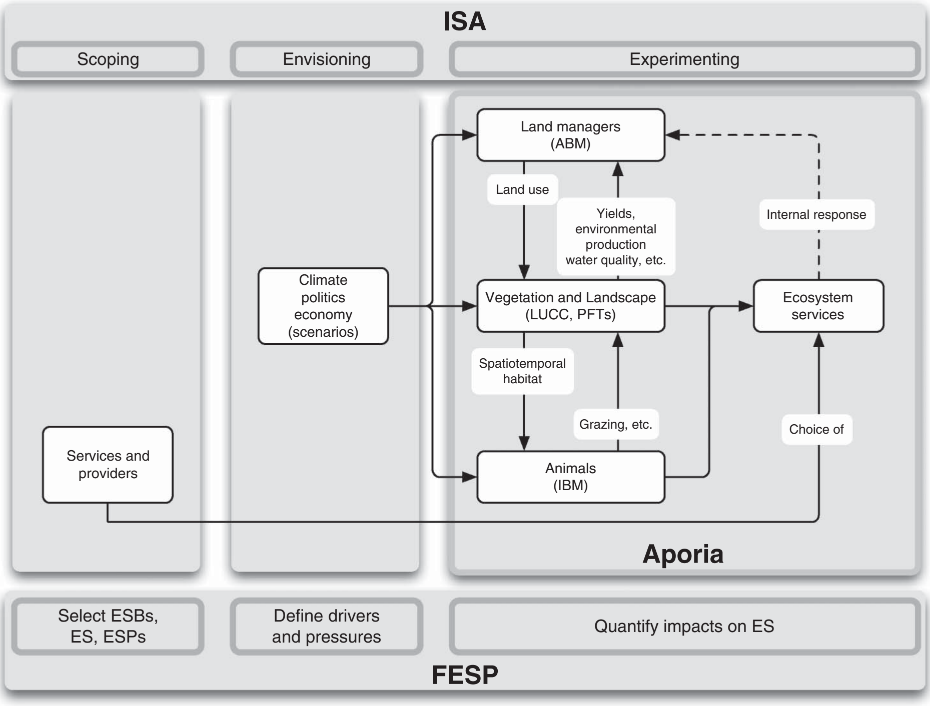

Figure 1. Contextualised structure of the conceptual model, showing relationships with both Integrated Sustainability Analysis (ISA) and Framework for Ecosystem Service Provision (FESP) frameworks.

- humans, in their role as land managers;
- landscape, on which their actions take place;
- organisms, which are affected by these actions.

There is also a need to work with the exogenous drivers, and here we suggest the use of integrated scenarios to make clear assumptions about the current and future state of these drivers and pressures.

Figure 1 shows the sub-models and interactions in the Aporia conceptual model[2]. To add some context to the modelling these are shown in relation to the initial stages of an integrated sustainability assessment (ISA) (Weaver and Rotmans 2006, www.mattise-project.net) and stages of a FESP analysis (Rounsevell *et al.* 2009):

- The ISA starts from a scoping phase, which defines the ES to be modelled, and the agents that will model them; similarly, the FESP analysis starts by defining the ES, providers and beneficiaries that are of interest.
- FESP analysis now stipulates that the drivers and pressures should be specified; in the ISA formulation, this is equivalent to the envisioning phase. Both result in the definition of a set of scenarios that will be modelled.
- Now, both formulations have a phase where these scenarios are modelled in terms of the ES identified in the initial stage.

Now, each sub-model will be discussed in turn, and then the necessary specification and couplings for the model as a whole will be laid out.

### *2.1. Land Managers*

In the Land Manager section of the model, we are concerned with generating the kinds of actions humans are likely to take on the landscape, in the context of the drivers and pressures related to the ES being investigated. This occurs most fundamentally through choices of land use and the actions necessary to support those particular uses.

To understand human decisions in their environmental and social context, it is necessary to explore the behaviours that underpin them. Social scientists and psychologists have developed several theories for this purpose, some of which have been used in LUCC studies (e.g. Parker *et al.* 2003).

The most widely cited theory describes the mainstream microeconomic view and is known as the 'Rational (actor) choice' theory (Manson 2006), which assumes perfect rationality, homogeneity and single-minded utility maximisation (Macal and North 2005). These assumptions offer analytical tractability (Myers and Papageorgiou 1991) and allow deduction; however, by neglecting the heterogeneity of human dimension and the limitations of both knowledge and cognition, this theory describes an ideal but unrealistic situation (Chase, Hertwig, and Gigerenzer 1998).

Empirical evidence shows that people often make suboptimal choices as defined by cost–benefit analyses (Beratan 2007), without always following the same decision-making pathway (Grothmann and Patt 2005). This stimulated the formulation of theories that deviated from the established rational norms.

Simon (1955) introduced the 'satisficing' model and the concept of 'bounded rationality', which accounted for physiological and psychological limitations (Chase 1998) and explained the mismatch between descriptive and normative behaviour (Dillon 1998). Related to this, (Tversky and Kahneman 1974, 1991) supported that people tend to make satisfactory, instead of optimal, choices as a result of the use of simple heuristics (i.e. representativeness, loss aversion) that limit their cognitive effort. In broader terms, however, some researchers support that making a suboptimal choice by using less cognitive effort should also be considered as optimisation (see Chase 1998; Jager, Janssen, De Vries, De Greef, and Vlek 2000).

Emphasis has also been placed on the complexity of the decision-making process, in the sense that decisions are products of one's economic, social, ecological and other imperatives (Faucheux and Froger 1995). Drawing from such statements, it was argued that the study of socio-ecological systems requires a more detailed conceptualisation of human behaviour (Beratan 2007), moving beyond basic economic assumptions. We will see the use of conjoint analysis for the representation of these complex preference structures in Section 4.2.

To represent a diverse range of complex cognitive processes, ABM is a logical choice. ABM has largely grown out of social science investigations into human behaviour, with some influence from the distributed artificial intelligence community (Hare and Deadman 2004). A common phenomenon in modelling is a progression from early, stylised and simplistic models to more complex, empirically grounded models (Sinclair and Seligman 1996), and ABM is no different. Although early models (Hägerstrand, Pred, and Haag 1967; Schelling 1971) were explicitly devised to have the simplest possible rules necessary to produce the desired behaviour, this allowed for a great degree of clarity in exploring theoretical hypotheses, but did not provide ways to use this new technique to investigate real-world problems; ABM has undergone an evolution towards increasingly complex, and empirically grounded, models (Janssen and Ostrom 2006; Clifford 2008) used to produce results of increasing specificity.

It is not necessary to specify the exact representations of cognition, but it is required to

- be representative of the human decision-making process;
- be sensitive to socio-economic scenarios;
- be parameterisable using data from social analysis, which can reasonably be carried out in a case study area;
- output the kind of land use decisions that humans make and react to the biophysical qualities of the land and climate.

### *2.2. Vegetation and Landscape*

Dynamic vegetation models (DVMs) simulate monthly or daily dynamics of ecosystem processes to 'grow' vegetation types at a location using a time series of climate data (solar radiation, temperature and precipitation), given the constraints of latitude, topography and soil characteristics. These models can be characterised for individual plant species, including food crops such as wheat or maize as well as tree species to estimate productivity and yield and other physical characteristics. Alternatively, they can model a simplified vegetation classification based on plant functional types (Smith 1997), which have often focused on patterns of global biomes (Prentice *et al.* 1992; Haxeltine and Prentice 1996). DVMs of natural vegetation tend to predict the spatial distribution of species and vegetation types through competition moderated by the species' physiological response to climate, for example, whilst crop (and forest) models focus on the effects of rotations and farmer decisions such as choice of planting date, crop density, fertilization and/or irrigation scheduling and harvest timing on yield predictions.

There are two main outputs that are needed from the vegetation sub-model. Firstly, the yields of crops is a vital driver for human decision making, as economics is often one of the strongest motivations, and this is highly dependent on the amount of a crop that can be grown on the land. Secondly, the vegetation acts as a habitat for the species that are explicitly modelled as living on it. A third output is the support that the vegetation provides for certain ES, in particular biodiversity.

This implies that two models may be necessary: one to model managed lands, based strongly around the question of yields, and a second to model competition and succession on unmanaged land.

### *2.3. Animals*

To effectively model the environmental and anthropogenic impacts on ES, it is necessary to consider the individual species and their interactions that contribute to services provision (Luck *et al.* 2009). A number of modelling strategies for predicting the distribution of species have been developed, which have often focused on the identification of a species' 'bioclimate envelope' or 'niche space' (see Pearson and Dawson (2003) for a comprehensive review). These methods are usually based around either empirical techniques that correlate current species distributions with climate or other environmental variables that vary over space and time (Box 1981; Berry 2002) or physiologically based approaches, generally implemented as DVMs (e.g. Prentice *et al.* 1992). The correlative models have been criticised for ignoring biotic interactions and assumes the relationship of a species distribution to its niche space is in equilibrium (Hampe 2004; Pearson and Dawson 2004), although species and LUCC interactions, together with dispersal and migration processes, are now being incorporated (Pearson, Pawson, and Liu 2004; Pearson and Dawson 2005). A number of LUCC patterns are leading to species' reductions and extinctions, together with their associated ES. In particular, agricultural conversion of natural landscapes to managed crop or pastureland results in wild species habitat loss and fragmentation, which can lead to reductions in total genetic variation, dispersal barriers and, for plants, the potential loss of key biotic interactions with pollinators and dispersal agents (Kerr and Currie 1995). In the United Kingdom it has been demonstrated that the range distribution of 21 farmland birds has contracted over three decades as a result of changes in management practices, including intensification (Chamberlain and Fuller 2000). Loss of hedgerows and field margins, and increased use of insecticides and herbicides, all contribute to biodiversity loss. Although birds and other animals are highly mobile, their specific foraging, breeding and nesting requirements can make them highly sensitive to LUCC and management regimes at the landscape scale.

From this we can see that there is a need for a finely detailed model of the interactions between animals and their habitats, with a fine spatial and temporal scale, which reacts to the management decisions of humans.

## 3. Conceptual model: scales, scope and couplings

Putting all of this together, we can address in a more detailed manner the inputs and outputs of each sub-model, and the scales at which they should be run. Figure 2 gives an overview of this.

Starting with the Land Managers, the decisions they make impose land uses on, and affect other biophysical characteristics of, the landscape. This is carried out by a Decision

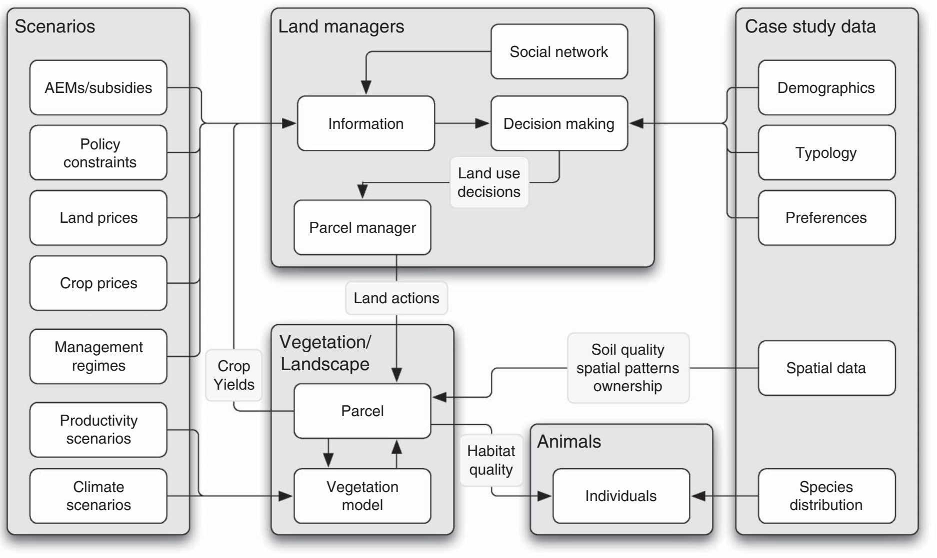

Figure 2. Detailed structure of the conceptual model.

Making module, based on information that represents their knowledge about the world. A large component of this information comes from the scenario assumptions about the model – what management regimes are known about, what subsidies are available, constraints on the quantities of crops, of amounts of inputs used, and so on. There is also a dynamic component to this, in that information about crop yields is updated in response to the results of modelling crop growth (under specific climate scenarios), and information can be obtained from the land manager's social network. This process of decision making is parameterised using social analysis data from particular case study regions: demographic information, typologies of behaviours and analyses of preferences.

Land use decisions are made at a fine spatial scale, applying to individual parcels – but a coarse temporal scale may only be changed on a yearly basis, or even at the end of a crop rotation. For this reason, it becomes useful to talk about a process of temporal downscaling. The Parcel Manager is responsible for taking these land use decisions, splitting them up into discrete actions on the land, and representing them on a daily timestep. This is the linkage that allows for human decisions at a coarse temporal scale to have effects on a much finer scale, and will be explored further in Section 5.

The Vegetation and Landscape sub-model holds the spatial structure of the landscape, as divided up into parcels. As well as encoding spatial structure, the Parcel representation also acts as an interface to the underlying model of vegetation and/or crop growth – taking the land actions and modifying the vegetation model appropriately, and collecting information about yields, and so on, to pass back to the land managers. The exact spatial configuration, ownership and biophysical properties of the parcels are clearly case study-based information.

Finally, this landscape structure is required as an input to the Animals model, to provide a dynamic habitat, influenced by human decisions. Although this is driven by a general model of how the species behaves, it is also likely that some case study-specific parameterisation is necessary.

This provides a conceptual model, which defines the inputs and outputs of the various sub-models, without restricting the mode of operation more than necessary – the intention is that different versions of each sub-model can be part of the experimental process, so that appropriate behaviour can be determined empirically for any given applications.

### *3.1. Scenario relationships*

As noted previously, the use of scenarios is important with modelling work – see also Rounsevell and Metzger (2010). Although this framework does not specify the manner in which scenarios should be generated, it is important to detail the mechanisms by which narrative storylines can be used to affect the model behaviour. Figure 3 illustrates a range of mechanisms by which scenario assumptions affect the behaviour of the land managers within the model. It is set up as follows:

- The outer circles on the diagram contain phrases that could be found in a typical narrative storyline, grouped according to the sub-models that they influence.
- The next layer is the sub-models; in a simple instantiation of the framework, these can be set up with preconfigured values, based on current values, trends and scenario assumptions. In more complex formulations, these can become dynamic models in their own right – for example, the inclusion of a stochastic Market model to represent uncertainty.

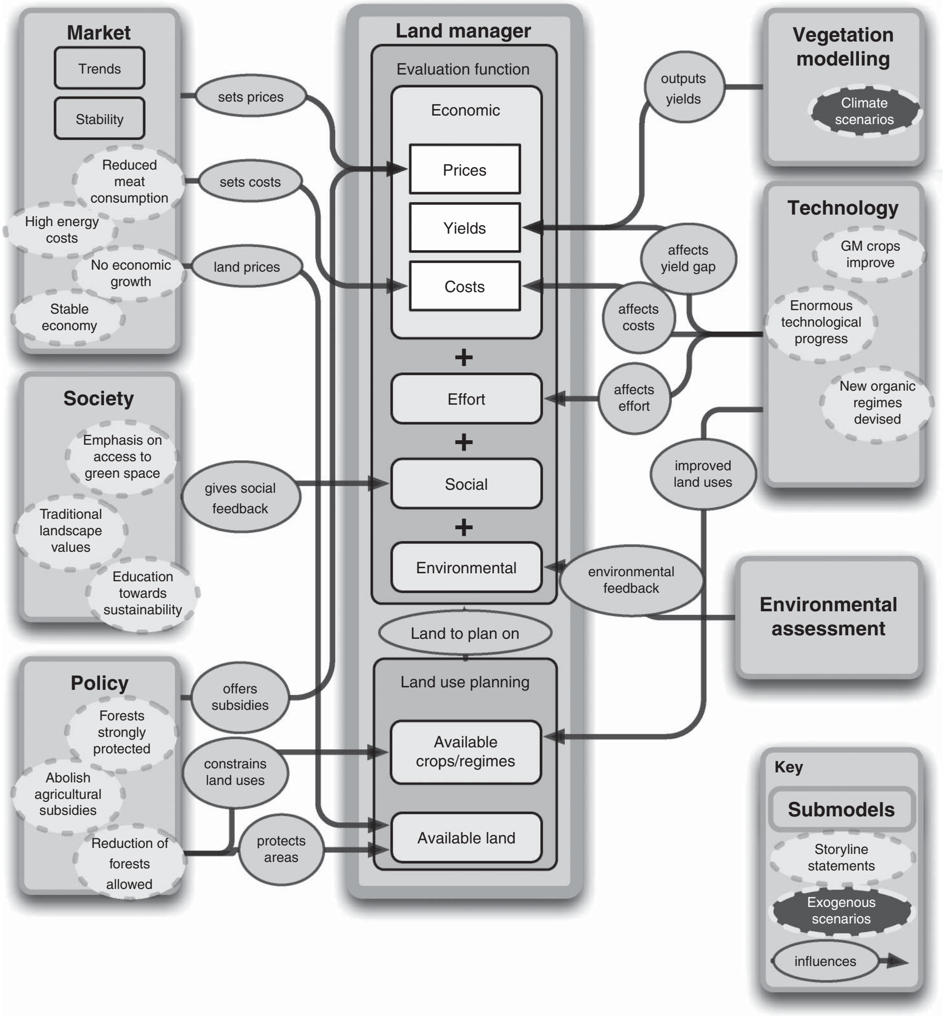

Figure 3. Scenario assumptions and their influences, through sub-model behaviour, on land manager decision making.

- The layer of arrows represent the mechanisms of action for the sub-models to influence various parts of the land manager's decision making. Some sub-models have effects in multiple places.
- The centre of the model represents the parts of the land manager's decision-making process that are influenced. These are either the preferences that the agents weigh up, or the range of options available to them when making decisions.

By specifying this grouping of scenario inputs, the process of designing storylines and converting them into drivers and pressures within the model should be made consistent and comparable, both to ensure consistency across scenarios for a single case study and to allow comparison across case studies.

## 4. Modelling of human behaviour

Section 3 defined the interfaces and some properties of the sub-models needed to create a coupled model. Here we investigate some of the concepts important to modelling the human behaviour in the model; in each case, we present an aspect of the model that needs to be filled in, and then describe a technique that has been, or will be, used to address that need.

### *4.1. Typologies of farmer behaviour*

Farm typologies are widely applied in rural research to assess the trends in farming practices, identify constraints to productivity for a specific development policy, identify beneficiaries of development projects and use as a technical tool for advising farmers (Gibon 1994, as mentioned in Gaspar 2007). They have also been increasingly developed to capture heterogeneity of farmers and diversity in farm decisions in agent-based land use research. This study follows the latter application to improve the representation of the agents and their decisions on sustainable farming practices and land use. To create models of behaviour that are generalisable, a deductive approach was taken:

- existing theories were selected as potential axes of classification;
- qualitative discourse analysis was used to classify farmers within the case study area on these axes;
- this analysis was used to refine the typological axes used.

In this case, the study was carried out on 22 farmers in the River Dyle's catchment study area (central Belgium). Two typologies were created, one relating to land use decisions and the other to the style of participation in agri-environmental measures (AEM).

For the first typological axis, the generic model of consumer behaviour from Jager, Janssen, and Vlek (1999) was used. The authors analyse non-economic motivations by introducing psychological rules to guide the behaviour of artificial agents in an experimental setting. Some agents in these models are fully rational and profit-maximising whilst others conserve limited cognitive resources by automating behaviour or by imitating the behaviour of others. The farmers were typified using information relating to the decisions for changing land use in the past, adaptive responses to the impacts of global environmental changes (e.g. decrease in yield due to climate change, decrease in prices due to global trade), influence of social network (e.g. neighbours' decisions) and responses to the changes in AEM technical and financial support. Applied to the domain of land use decision making, four types of cognitive strategies were identified: adaptive, imitative, conservative and innovative.

The second typology was based on the the attitudinal work of Fish, Seymour, and Watkins (2003) regarding AEM implementation. Among the information collected to build the former typology type include motivations for applying AEM, practical experiences in AEM application, suggestions for improving AEM design and distribution, role of communications with advisors, other farmers and the public, and future intentions on AEM application.

Four types of AEM participation styles were identified from the interview results and based on the typology proposed by Fish *et al.* (2003), that is: opportunist, modifying, catalysing and engaged participation. As in Fish *et al.* (2003), these styles are by no means mutually exclusive: farmers frequently adopt different attitudes depending on the AEM implemented. The take-up of AEMs is singled out explicitly, as these can have a large impact on ES – see Section 5 for an example. This provides for an *inductive* classification of farmer behaviour, based on the way in which decisions are made; for a more individualistic analysis of the preference structure of the farmers, we turn to conjoint analysis.

### *4.2. Conjoint analysis of preferences*

Conjoint analysis is a technique widely used in different scientific fields including psychology, transport, economics and environment to transform subjective choice responses into estimated parameters. Farber and Griner (2000) provide a summary of the application of conjoint analysis for environmental valuation. The subjective choices for non-marketed or non-economic goods and services such as those provided through the natural environment or ecosystem are valued in conjoint analysis as preferences. Conjoint analysis is suitable for analysing decisions, particularly for understanding the process by which individuals develop their preferences for products or services (Sayadi, Gonzalez-Roa, and Calatrava-Requena 2005), assuming that the product can be described by setting levels for a collection of attributes, and that the consumer's decision is based on these attributes (Sayadi, Gozalez-Roa, and Calatrava-Requena 2009). When selecting attributes, they must cover all the factors relevant for a given decision task, be independent of each other and have compensatory relation between each other (Becker, Czap, Poppensieker, and Skotz 2005). In case of land use decisions, the attributes must consider not only economic gain and costs but also social and environmental.

The first step in conjoint analysis is selecting the combinations of attributes and levels, which are the basis of the respondents' choices. Based on this and other constraints, an appropriate conjoint analysis method can be selected, and the design can be checked based on the expected number of respondents.

Based on the results of a set of interviews with the farmers, we selected the most relevant attributes in their land use decisions, and decided on a choice-based conjoint questionnaire (Orme 1998). Table 1 presents an example of the choice tasks that farmers will be asked to complete. By including manageable numbers of attributes and levels, the choice tasks in the survey questionnaire can be easily conducted through paper-and-pencil survey – this is important because many farmers do not have Internet access to answer computer-administered surveys. We validate the reliability of the survey design using statistical tests and its relevance to land use decisions through field testing with local officials and farmers.

Once the land managers can be modelled, it is possible to begin to quantify the effect of their behaviour on the animal species that inhabit the landscape they manage.

Table 1. Example conjoint choice task.

| Attributes | Option 1 ☐ | Option 2 ☐ | Option 3 ☐ | Option 4 ☐ |
|---|---|---|---|---|
| Source of income | Crop production | Livestock production | Non-Food production | Environment managemet |
| Required effort | No added work | More work | Less work | More work |
| Social Feedback | No feedback | Negative feedback | No feedback | Positive feedback |
| Environment impact | Degrade environment | Degrade environment | Maintain environment | Enhance environment |
| Level of risk | Average risk | Low risk | High risk | Low risk |
| Change in profit | No change | +10% | No change | −10% |

## 5. Individual-based modelling of skylark behaviour

To quantify the effect of human behaviour on wild animals – which impact on both biodiversity and cultural ES – a model of species behaviour that is sensitive to land management decisions is necessary. As argued in Section 2.3, there is a need to go beyond the correlative approaches of niche modelling and bioclimatic envelopes and create a model that can be applied at a fine spatio-temporal scale, and interacts strongly with landscape features.

In this case, we looked at the skylark (*Alauda arvensis,* L.). It is a common cropland bird across Europe but its populations have suffered from agricultural intensification and changes in cropping patterns. The objective of this sub-model is to estimate the reproductive capacity of the species within a human-induced changing landscape. To do this, efforts are made to model individuals' variation and their interactions with each other and a spatially explicit landscape.

A literature survey (Delius 1965; Wilson, Evans, Browne, and King 1997; Poulsen, Sotherton, and Aebischer; 1998; Chamberlain and Crick 1999; Donald Evans, Buckingham, Muirhead, and Wilson 2001; Boatman *et al.* 2007) provides the first step towards a parameterisation of the model and ensuring it reflects patterns from nature (Grimm 1999). However, there are issues with applying parameters from the literature that must be addressed (Railsback 2001), so the parameterisation was enhanced by a local field survey and expertise and focused on storylines related to the interactions between land use decisions and skylark population.

Studies have shown the highly selective preference of this species for a certain vegetation structure, for particular land use and for open habitat (Wilson *et al.* 1997). This defines strong relationships between agricultural practices and the length of the breeding window. As an example the skylarks require vegetation heights between 20 and 50 cm for nest construction; rotational cropping ensures that there are crops that are planted at different times, with different growth rates, so there is a wide range of times when the appropriate vegetation height is present during the breeding period, while monoculture reduces the amount of time suitable vegetation is available (Wilson 1997). This relates to the daily timestep and parcel-based landscape model suggested previously for modelling interactions. Similarly the degree of intensity is important, as it relates to insect density, which provides food for the skylarks (Cole 2005).

Within the model, this results in a causal chain from scenario assumption through to skylark biology as follows (see Figure 4):

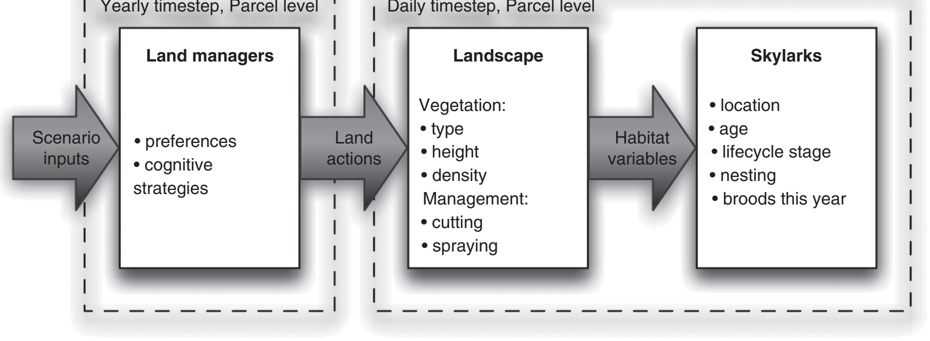

Figure 4. Causal chain from human behaviour through to biological responses of skylarks.

Table 2. Human actions and their effect on the skylark IBM.

| Human action | Landscape parameter | Effect on skylarks |
|---|---|---|
| Sowing time | Vegetation height (daily) | Nesting suitability |
| Silage cutting | Vegetation height | Nesting suitability, instant mortality |
| Pesticide spraying | Pesticide sprayed | Food abundance |
| Crop choice | Vegetation type, invertebrate assemblages | Nesting suitability, food abundance |
| Vegetation type | Nesting suitability, food abundance | |

- Scenario inputs determine the decision-making context: regimes available, yields, prices, costs, restrictions, and so on. This delimits the set of possibilities to choose from and affects the preferences that are used to decide between different options. In particular, agri-environmental schemes to be trialled – such as skylark plots (Morris 2004) and field margins – can be introduced as part of the scenario. These scenario inputs change at most on a yearly timescale.
- Land managers make land use decisions. This can be about what crops to grow when, timings of sowing and harvesting and the intensitivity. This happens at a yearly timescale and is dependent on the preference structure and cognitive capabilities discussed previously.
- These decisions are temporally downscaled (by the parcel manager), and applied to the landscape. This results in actions that are carried out on a specific day of the year, and affect both the land use of each parcel and any simulated vegetation growing there.
- The results of these actions affect a vegetation-modelling component, which provides the habitat in which skylarks exist. This primarily consists of vegetation type, height and density, along with markers for certain types of management. This is maintained on a daily basis, for each parcel within the landscape.
- Skylarks are modelled as individuals, each having an age, a lifecycle stage, a breeding status and a location. For skylarks of breeding age, the model also tracks whether they have a suitable nest site – based on the time of year, vegetation structure and presence of other skylarks and the number of broods produced so far. If there is a breeding pair with a suitable site, then eggs are produced, which go through the lifecycle stages until they are adult birds. At each stage, a different mortality rate is applied, which may be affected by environmental factors such as food abundance. There are also human practices, such as cutting grass for silage, which result in instant mortality for pre-juvenile skylarks.

Table 2 sums up some of these chains from human action, through the landscape modelling to skylark biology.

Finally, three outcomes are tested in model simulations to assess the relative impact of land use change on the breeding capacity of skylarks: i) number of suitable nesting sites, ii) number of broods within a breeding season and iii) resulting population.

## 6. Discussion

In this article, we have developed a conceptual model for using ABM to assess ES, by dynamically modelling SES. We have also explored case studies focusing on the human behavioural component of the model, and the reactions of animal species to this.

By specifying human behaviour in terms of inputs and outputs of the sub-model, it is possible to compare different approaches to the behavioural modelling. The strategy-oriented approach of the initial farmer classification leads naturally towards a rule-based representation of the non-idealities of human behaviour; alternatively, the conjoint study of farmer's attitudes and preferences allows for the idea of optimisation over a rich preference space. By having the possibility for entirely different modes of behaviour in the model, it is possible to see which most closely models the observed behaviour, and draw conclusions about what aspects of human behaviour need to be represented. A large part of the future work with this conceptual model will be the comparison and possible hybridisation of these approaches, to empirically determine appropriate models for the particular case studies and individuals within them.

The typological assignment from interview transcripts can in itself can be considered a useful output building up a detailed picture of the reasoning behind land use decisions. In the context of model creation, this provides empirical support that the theoretical models of behaviour used to create the typology are relevant to modelling human behaviour. The benefit of working inductively within previously defined behavioural theories is that relatively general rules governing behaviour can be created – much as the Consumats (Jager *et al.* 1999) had clearly defined behaviours relating to the different cognitive strategies. However, to orient the model towards case study use, it should be possible to represent the needs and desires of individuals in a more continuous space, which is where results from the conjoint analysis will be used, to create a multidimensional preference space, and allow a complementary, deductive approach to understanding the behaviour of land managers.

The final case study – the skylark model – provides a complete illustration of how the conceptual model can be used to analyse the effects of human actions on ES. The socio-economic decisions made by the human farmers affect the landscape, which in turn affects the breeding success and population of skylarks. Furthermore, the role of policy and the use of AEMs can be clearly followed through to the ecological impacts. It can be seen that landscape factors that are essential to this capacity are clearly related to human management in an agricultural context, and that the management plans, especially participation in AEM, are influenced by biophysical, economic and political factors along with personal attitudes and goals. Consequently, skylark population impacts are assessed as a result of human behaviour grounded within the larger socio-economic context.

Finally, one of the conceptual models will be in whether a complete model can be created that addresses the necessary questions. The case studies used here do not detail the operation of the entire model – in particular it is clear that there has been little discussion of the vegetation-modelling component. This is an area that is part of the ongoing work, and finding a suitable technique for modelling vegetation that provides both accurate yields for the socio-economic motivations of land managers and the detailed biophysical states required for species habitat modelling is expected to be a challenge.

In summary, we have outlined a framework for using ES to analyse SES, in an operationalised manner; by focusing on the modelling of the interdependence between humans and their environment, we hope to prompt a move beyond discourse into a more pragmatic investigation of SES.

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## Notes

1. The literature on SES uses the terms social- and socio-ecological in an apparently interchangeable manner; in this article we use socio-ecological.
2. Aporia means a state of confusion or tension arising from inconsistent but equally plausible premises; the model is so named to indicate the tensions between different preferences and outcomes that the agents hold.

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