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A Bayesian sensitivity analysis applied to an Agent-based model of bird population response to landscape change[☆]

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ABSTRACT

Agricultural land management has important impacts on land use and vegetation that can rapidly induce ecosystem change. Birds are often used as indicators of such impacts of landscape change on ecosystems. However, predicting the response of birds to changes in their environment is an ongoing challenge. Agent-based models (ABMs) have the potential to provide useful insights but have not been widely used in such studies to date. This paper illustrates the use of agent-based modelling for policy decision-making, using the case study of the impacts of the removal of set-aside land on Skylark populations in Denmark.

In order to address the importance of critical interpretation of ABMs, we introduce a novel methodology with which to analyze the sensitivity of an ABM, Bayesian Analysis of Computer Code Outputs (BACCO). BACCO constructs an emulator of the model in order to provide a rapid and thorough sensitivity analysis. This allows us to identify input parameters in the model that require more rigorous parameterization, as some parameters are highly sensitive and are found to produce spurious results when varied even a small amount.

1. Introduction

Agent-based models (ABMs), such as the model presented here, are often large and complex simulations with significant data requirements (Parry and Bithell, 2012). As a result, there will usually be numerous assumptions and unknown inputs. The complexity of the model may also lead to problems in communicating the model, validating the model behavior or conducting sensitivity analysis (Grimm et al., 2006). We present the novel use of Bayesian Analysis of Computer Code Outputs (BACCO) (Kennedy et al., 2006; O'Hagan, 2006; Oakley and O'Hagan, 2004) applied to an ABM of Skylarks in an agricultural landscape to analyze model uncertainty as a form of model assessment and validation.

Sensitivity analysis of computer models is the study of the relative influence of individual inputs, or groups of inputs, on a code output. A good analysis can contribute to the overall interpretation of the model, increase its credibility across a range of possible input scenarios, or uncover errors. A crude method is simply to vary one input at a time, but results are then dependent on the value of the other fixed inputs and can be highly misleading (Saltelli and Annoni, 2010). Global methods are much more rigorous as they account for variations in multiple parameters simultaneously (Oakley and O'Hagan, 2004), but the computational cost of such methods can be prohibitive. The acronym BACCO has been used to describe a general class of methods for Bayesian Analysis of Computer Code Outputs (Hankin, 2005; O'Hagan, 2006). With BACCO sensitivity analysis, the number of code runs can be dramatically reduced compared with traditional Monte Carlo (MC) sensitivity analysis, making it much more widely applicable in practice.

ABMs have the potential to provide useful insights on the interaction between avian ecology and landscape change (Rodriguez et al., 2006; Stillman and Goss-Custard, 2010; Topping et al., 2010a). The impact of human decision making regarding land use and management on the environment is a key factor in contemporary ecosystem change (Boatman et al., 2007; Haines-Young, 2009; Haines-Young et al., 2003; Robinson and

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Sutherland, 2002). Birds are often used as indicators of impacts on biodiversity because they are readily observed and easily monitored, as well as sensitive to anthropogenic changes (Gregory and van Strien, 2010). Advantages of ABMs over more 'traditional' population-based or autoecological approaches include the ability to simulate the effects of new land use types with given properties and landscape structure (as model drivers operate at a lower level) (Schumaker et al., 2004), examine impacts at multiple landscape scales (Walters, 2007), incorporate temporal variability in habitat suitability (Parry et al., 2006) and relate population density fluctuations to underlying dynamics (Elderd and Nott, 2008). The capacity of individuals to evolve or adapt their behavior in response to changes in the environment may enable these models to give greater understanding of how and why landscape-scale distributions emerge.

As a result of changes in the system of subsidy payments and declining grain stocks, the European Commission decided to abolish set-aside in 2008. Set-aside was an important habitat for Skylarks, and the highest densities on arable land have been found on set-aside (Chamberlain et al., 1999; Donald et al., 2001; Wilson et al., 1997). The withdrawal of set-aside was therefore considered likely to have significant impacts on this species (Boatman et al., 2010). Empirical data does not exist to measure the Skylark population response to the novel landscape context, therefore a mechanistic simulation modelling approach is required. A case study addressing the implications of the abolition of set-aside for Skylarks in Denmark is used to demonstrate the application of an ABM to policy-relevant issues, building on an existing agent-based Skylark model (Topping et al., 2003). This aims to simulate the possible effects of set-aside removal on Skylark populations in a Danish landscape.

Despite some clear advantages of using an Individual- or Agent-based modelling approach as described above, there has been some reluctance to use this form of modelling, notably by policy-makers. According to Smith et al. (2009), there are three main objections to the use of any kind of model for policy development. Firstly, unbelievable results may arise from errors in the model, if the model is not robust. This will have a negative impact on the confidence of policy-makers in the model. However, unexpected results may not necessarily disprove the whole model and may even lead to new insights, thus models should not be simply dismissed if some results are unexpected. Secondly, a common criticism is a lack of validation. A full analysis of the uncertainty and sensitivity of the model is important to understand the model and for policy-makers to confidently trust model results (Castaings et al., 2012), in addition to a comparison with real-world data, if available. Thirdly, a model may be thought too complex or maybe does not include some critical component. Model complexity may be a barrier to the use of models to inform policy decisions, as clarity is important for decision-making. Therefore, thorough model analysis and clear, comprehensive model communication will lead to greater acceptance of models to inform policy decisions. We believe the type of sensitivity analysis we present in this paper goes some way towards addressing this need for thorough model analysis.

2. Application of the agent-based ALMaSS model to simulate set-aside removal

2.1. ALMaSS model overview

The Skylark agent-based landscape model is a component of the ALMaSS model framework (Topping et al., 2003), implemented using the object oriented programming language C++, and available as an open source project on CCPForge (Topping, 2011c). The ALMaSS landscape model provides a temporally and spatially explicit landscape simulation model, which simulates land use change at the scale of a small region, taking into account farming decisions, agricultural processes and vegetation growth in detail, although holding socio-economic drivers fixed (Fig. 1). ALMaSS includes a farm management decision simulator that is capable of providing information on sequence, intensity and timing of farm activities. The model has been used beyond its original specification in Denmark (Topping et al., 2003) to look at landscape change (Jepsen et al., 2005), evaluate the impacts of mechanical weeding alternatives to pesticides (Odderskaer et al., 2006), evaluate pesticide impacts (Odderskaer et al., 2003), predict impacts of policy changes to pesticide taxation (Topping, 2005) and to evaluate simple scenarios of climate change (Topping, 2012). Recent studies use this Skylark model and ALMaSS to evaluate energy maize impacts in Germany (Gevers et al., 2011) and organic farming (Topping, 2011a).

ALMaSS simulates farm management decisions by defining farm units and farm types with specific crop rotations. The farm management decision simulator is capable of providing information on sequence, intensity and timing of farm activities. For each farm unit 'Crop-husbandry plans' are used to define a series of events such as harvest. Decisions are based on the weather and history of management only, not economics. An evaluation of the consequences of land use strategies was conducted by Jepsen et al. (2005) using the ALMaSS framework (the underpinning landscape simulator) and including the Skylark model used by this study. As

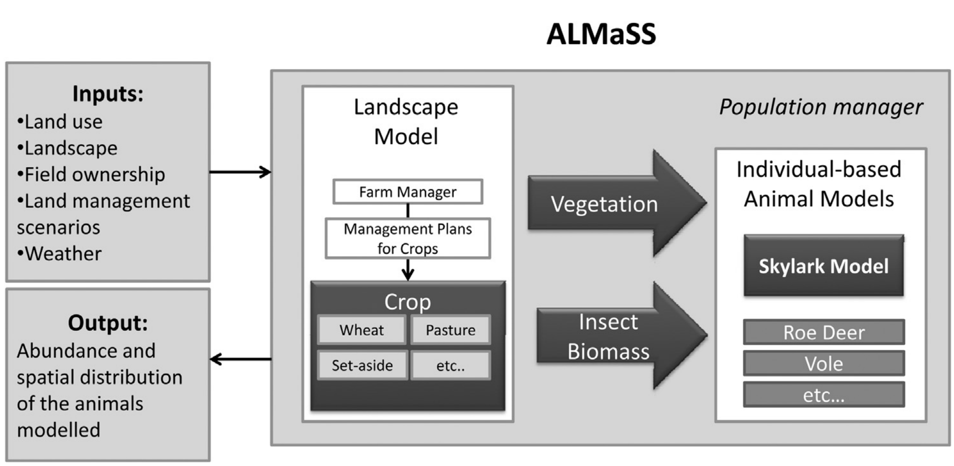

Fig. 1. Overview of the ALMaSS simulation framework, highlighting the Skylark and Landscape modelling components used in this study, with arrows showing the key landscape properties that influence Skylark population dynamics (after Jepsen et al. (2005)).