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Review

Representation of decision-making in European agricultural agent-based models

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A B S T R A C T

The use of agent-based modelling approaches in ex-post and ex-ante evaluations of agricultural policies has been progressively increasing over the last few years. There are now a sufficient number of models that it is worth taking stock of the way these models have been developed. Here, we review 20 agricultural agent-based models (ABM) addressing heterogeneous decision-making processes in the context of European agriculture. The goals of this review were to i) develop a framework describing aspects of farmers' decision-making that are relevant from a farm-systems perspective, ii) reveal the current state-of-the-art in representing farmers' decision-making in the European agricultural sector, and iii) provide a critical reflection of underdeveloped research areas and on future opportunities in modelling decision-making. To compare different approaches in modelling farmers' behaviour, we focused on the European agricultural sector, which presents a specific character with its family farms, its single market and the common agricultural policy (CAP). We identified several key properties of farmers' decision-making: the multi-output nature of production; the importance of non-agricultural activities; heterogeneous household and family characteristics; and the need for concurrent short- and long-term decision-making. These properties were then used to define levels and types of decision-making mechanisms to structure a literature review. We find most models are sophisticated in the representation of farm exit and entry decisions, as well as the representation of long-term decisions and the consideration of farming styles or types using farm typologies. Considerably fewer attempts to model farmers' emotions, values, learning, risk and uncertainty or social interactions occur in the different case studies. We conclude that there is considerable scope to improve diversity in representation of decision-making and the integration of social interactions in agricultural agent-based modelling approaches by combining existing modelling approaches and promoting model inter-comparisons. Thus, this review provides a valuable entry point for agent-based modellers, agricultural systems modellers and data driven social scientists for the re-use and sharing of model components, code and data. An intensified dialogue could fertilize more coordinated and purposeful combinations and comparisons of ABM and other modelling approaches as well as better reconciliation of empirical data and theoretical foundations, which ultimately are key to developing improved models of agricultural systems.

1. Introduction

Governments strongly influence and support the agricultural sector in Europe and there is increasing interest in a critical evaluation of these policies. In this context, reliable explanatory models of agricultural systems are of key importance since they allow evaluations of effectiveness and efficiency of policy measures where empirical data is not (yet) available e.g. in climate change impact studies, modelling

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counterfactual scenarios of policy changes, or future market conditions. Understanding how farmers take decisions, including anticipation strategies, adaptive behaviour, and social interactions is crucial to develop such models (Janssen and Ostrom, 2006; Meyfroidt, 2013; Berger and Troost, 2014).

In recent years, agent-based models (ABM) have gained increasing popularity for modelling agricultural systems and the impacts of policies (e.g. Nolan et al. 2009, Groeneveld et al., 2017, Kremmydas et al., 2018). Agent-based modelling represents a process-based "bottom-up" approach that attempts to represent the behaviours and interactions among autonomous agents through which agricultural systems are evolving and thus to simulate emergent phenomena without having to make *a priori* assumptions regarding the aggregate system properties (Brown et al., 2016a; Helbing, 2012; Magliocca et al., 2015). Thus, agent-based modelling is a suitable tool for improving the understanding of farmers' behaviour in response to changing environmental, economic, or institutional conditions, particularly on the local level (An, 2012; Magliocca et al., 2015).

Agent-based modellers often choose to build new models from scratch (O'Sullivan et al., 2016) and take varying approaches, from microeconomic models to empirical and heuristic rules (An, 2012; Schlüter et al., 2017), based on whichever suits their purposes best. As a consequence, empirical data on farm decision-making collected for model building is often specific to one model, one geographic region, and the particular processes being represented. The key challenge is to ensure that, for sake of parsimony, the representation of decision-making in agricultural ABM is equipped with those properties and behavioural patterns of the farmer that are relevant for a given purpose, and no more or less (Balke and Gilbert, 2014).

The representation of farmers' decision-making crucially depends on the phenomena to be simulated and the purpose of the study. Modellers may abstract or ignore system properties in a specific modelling endeavour even though the corresponding mechanism is important from a conceptual perspective. Because no single approach is best suited to represent decision-making in general, comparing different research efforts can help to identify which particular agent decision-making representations are appropriate for particular model purposes (Parker et al., 2003). This could support more coordinated and purposeful combinations of ABM and other hybrid modelling approaches in the agricultural sector, which would lead to improved models of agricultural systems (O'Sullivan et al., 2016).

Model comparisons and reviews are frequent in land-use and land-cover ABM (Parker et al., 2008a; Parker et al., 2008b) and recently more generic and flexible modelling approaches such as agent functional types (Arneth et al., 2014; Murray-Rust et al., 2014a) or agent-based virtual laboratories (Magliocca et al., 2014) have emerged. While these comparisons and reviews are very useful, they do not provide an in-depth analysis of specific models and its functionalities. Notably, a proper analysis and comparison of agents' decision-making in agricultural ABM with a specific focus on European agriculture and its specific policy context is lacking. The European agricultural sector with its single market and its common agricultural policy (CAP), fundamentally anchored in the concept of multifunctionality, provides a specific setting of economic and institutional conditions that allows for a meaningful comparison of different approaches in modelling farmers' behaviour. This setting is particularly distinct from that of subsistence farming in developing countries or very large farms in the US or Australia. With many researchers currently engaged in agricultural ABM in Europe, there seems to be a fruitful basis for more in-depth comparison of models within the same research domain and research focus.

Thus, here we reviewed existing ABM in the European agriculture context with a specific focus on the implementation of the farmers' decision-making process. The research questions are:

i) What are the specific properties of European farmer households that are believed to influence their decision-making?
ii) Which levels and types of decision-making mechanisms are represented in European ABM?
iii) Are the represented decision-making mechanisms related to specific problem domains in agricultural systems?

The review provides a first entry point for agent-based modellers, the broader community of agricultural systems modellers and data-driven social scientist for the re-use and sharing of model components and codes as well as for the identification of meaningful model comparisons in the context of farm systems analysis. This is the key to develop comprehensive models of agricultural systems and their use in ex-ante or ex-post agricultural policy evaluations. The paper is structured as follows. In a background section, we summarize existing reviews on decision-making in ABM and outline a farm-systems perspective on decision-making in agricultural ABM. We then describe the review process and the levels and decision types used for the description of the models. In the Results section, we illustrate how the conceptualisation of decision-making varies by research question in agricultural ABM. Finally, we discuss our results with respect to ABM in general and outline future prospects for decision-making in agricultural ABM.

2. Conceptual background

2.1. Description of decision-making in ABM

Several recent reviews have classified the types of decision-making used in ABM in social-ecological or human-nature systems, either from an operational or a theoretical perspective. In his review, An (2012) classified the different theoretical approaches into nine decision models, ranging from microeconomic mechanisms to psychological and cognitive models. The ODD protocol is currently the standard for describing ABM, with a specific extension for human decisions ODD + D (Müller et al., 2013). The ODD protocol is structured in three basic elements i.e., overview, design concepts and details (Grimm et al., 2006; Grimm et al., 2010). According to ODD + D, the individual decision-making should be described by making explicit the subjects and objects of decisions, the levels of decision-making, rationality/objectives, decision rules and adaption, social norms and cultural values, spatial aspects, temporal aspects, and uncertainty. The protocol has already been used to compare different ABM land-use models (Groeneveld et al., 2017; Polhill et al., 2008) and agricultural ABM (Kremmydas et al., 2018). The MR POTATOHEAD[1] framework has also been used to compare agent-based land-use models (Parker et al., 2008a, 2008b). The framework distinguishes six conceptual classes; information/data, interfaces to other models, demographic, land-use decision, land exchange, and model operation. Compared to the more general ODD, MR POTATOHEAD enables a more detailed comparison of *land-use* related ABM.

With a stronger focus on theoretical aspects of the decision-making, the MoHuB (Modelling Human Behaviour) framework provides a tool for mapping and comparing behavioural theories of individual decision-making of a natural resource user (Schlüter et al., 2017). MoHuB distinguishes between the individual and its social and biophysical environment, which interact through 'perception' of the environment and agents' 'behaviour'. The actual 'selection' process of behaviour depends on the 'state' of the agent, which includes its goals, values, knowledge and assets as well as its 'perceived behavioural options'. The 'evaluation' of the consequences of an agent's behaviour on its 'state' closes the loop. The authors use this framework to describe different theories, including the concepts of *Homo economicus*, bounded rationality, theory of planned behaviour, reinforcement learning, descriptive norms, and prospect theory (see Schlüter et al., 2017). Balke and Gilbert (2014)

[1] MR POTATOHEAD: Model representing potential objects that appear in the ontology of human environmental actions and decisions