A review of Agent Based Modeling for agricultural policy evaluation

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Review

A review of Agent Based Modeling for agricultural policy evaluation

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ABSTRACT

Farm level scale policy analysis is receiving increased attention due to a changing agricultural policy orientation. Agent based models (ABM) are farm level models that have appeared in the end of 1990's, having several differences from traditional farm level models, like the consideration of interactions between farms, the way markets are simulated, the inclusion of agents' bounded rationality, behavioral heterogeneity, etc. Considering the potential of ABMs to complement existing farm level models and that they are a relatively recent approach with a growing demand for new models and modelers, we perform a systematic literature review to (a) consolidate in a consistent and transparent way the literature status on policy evaluation ABMs; (b) examine the status of the literature regarding model transparency; the modeling of the agents' decision processes; and the creation of the initial population.

1. Introduction

Agricultural policies are moving away from market intervention measures toward a combination of voluntary and compulsory aids on top of basic flat rate support measures related to farm features, its environmental performance and capacity to provide ecosystem services. Consequently impacts of policy measures depend on the specific farm characteristics. So getting insights at disaggregated level and spatial scale becomes relevant for both policymakers and researchers; consequently farm scale policy analysis is receiving increased attention (Langrell et al., 2013).

Berger and Troost (2014) summarized the requirements that farm-scale models need to fulfill in order to provide useful insights within this new policy context: sufficient detail of farm management and agronomic conditions; model the heterogeneity in behavioral constraints and behaviors; include farm interactions; incorporate spatial dimension; consider farm-environment interactions and feedback; move from a comparative-static to a comparative-dynamic analysis; moderate data requirements connected to existing data sources; employ comprehensive sensitivity and uncertainty analysis. They conclude that ABMs have the potential to meet the above requirements and thus can complement existing simulation approaches.

Also, in a recent review paper, Reidsma et al. (2018) examined the development and use of farm models for policy impact assessment. Agent Based models (ABM), about 15% of all 184 papers considered, were found to have the potential to provide important additions to farm level mathematical programming models.

Agent based models in agricultural economics have appeared in the end of 1990's. Some of the early adopters were the CORMAS group which employed a multi-agent approach to study renewable source management within an agricultural systems context (Bousquet et al., 1998). Balmann (1997) used a cellular automata approach for modeling structural change of agricultural production systems; and Berger (2001) used a spatial multi-agent programming model to assess policy options in the diffusion of innovations and resource use changes. The latter two approaches, which were policy evaluation oriented, can be considered descendants of the recursive mathematical programming (MP) approach, as the initial ABMs included a typical MP production/investment problem coupled with a land market module that was solved iteratively. The innovative elements were: the ability to include farms' interaction and in this way to evaluate the direction of the structural change (farm growth/shrinking, farm entry/exit) and the explicit consideration of the spatial dimension.

The additions of ABMs to traditional farm level microeconomic

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models,[1] in the conceptual level, are well summarized in Nolan et al. (2009) and are shown in Fig. 1. Farm and consumer heterogeneity, spatial location and the consideration of interactions between farms and/or consumers (social networks, land markets, imitation, etc.) are presented as a distinctive feature of ABMs. Moreover in the case of traditional farm models, market outcome is the combination of the aggregate supply and demand functions while in the ABM case, market is simulated by means of individual transactions. Additionally, although traditional farm level models can potentially do so, Nolan et al. (2009) note that since ABM is most often used in cases where equilibrium conditions either cannot be identified or analytically solved, they generally relax the assumption of full rationality. This allows the assumption that economic agents facing limited information and/or information processing capacity and finite resources. Furthermore they can be endowed with adaptive mechanisms and learning capabilities.

In a 2007 review, Matthews et al. note that “there is an increasing pressure from funding agencies to develop (Agent Based Land Use Models) tools that are of practical use by end-users and other stakeholders”. Later in a methodological overview of agricultural and farm level modeling development and implementation, Langrell et al. (2013) found that although there is a substantial increase of ABMs models over time, “a large number of existing farm level models are developed for specific purposes and locations and are not easily adaptable and reusable (for policy evaluation)”.

Thus, considering the potential of ABMs to complement existing farm level models and that they are a relatively recent approach with a growing demand for new models and modelers, the aims of the paper are twofold: (a) to consolidate in a consistent and transparent way the literature status on ex-ante policy evaluation ABMs; (b) to examine the critical aspects to gain more acceptance from the wider farm modeling community.

Both targets of the paper are pursued by employing a systematic literature review (SLR) approach, for related publications since 2000. The remainder of the paper is organized as follows. Section 2 describes the SLR method used in this study. Section 3 presents the results of the SLR and the discussion of the findings; Section 4 concludes the paper.

2. Literature review design

2.1. Review protocol

The first step of the review protocol is to develop a transparent search strategy for discovering papers that are potentially related to ABM applications in the agricultural policy evaluation domain. Selection criteria are used to classify papers in groups. This addresses the first target of the paper, i.e. a consolidation of the existing ABM policy literature.

Then we clearly and explicitly specify research questions related to the second aim of the paper; an examination of the most critical aspects for further adoption of empirical ABMs from farm modelers. We use a structured process to extract all information needed to address the review questions in a meaningful way.

2.2. Search strategy and selection criteria

Search is confined to papers written in English and published in peer-reviewed journals between 2000 and 2016 and either in title, abstract or keywords include one or more of “agent-based”, “agent based”, “abm”, “multi-agent” or “multi agent” and any word beginning from “polic” and in title any word beginning from “farm”, “agricul”, “biodivers” or “crop”. This is equivalent to the following SCOPUS search command:

SRCTYPE (j) AND (TITLE-ABS-KEY ("agent-based" OR "agent based" OR "abm" OR "multi-agent" OR "multi agent") AND (TITLE-ABS-KEY (polic*) OR INDEXTERMS(polic*)) AND (TITLE-ABS-KEY (farm*) OR TITLE-ABS-KEY (agricul*) OR TITLE-ABS-KEY (biodivers*) OR TITLE-ABS-KEY (crop*))) AND (PUBYEAR > 1999) AND (PUBYEAR < 2017) AND LANGUAGE (english)

The search produced 176 documents that were further refined based on the criteria detailed below:

Criterion 1: the relevance to the Agent Based Modeling (criterion 1a) and Agriculture domain (criterion 1b). Based on abstract inspection and on full text inspection when necessary we removed 11 papers that were not agent based models but rather were just mentioning the term (NOT ABM). We removed 5 papers where ABM was a fraction of a larger model and thus there were not many details on the ABM implementation (PARTIALLY ABM). We removed 29 papers that were dealing with marine or coastal areas, urban areas, etc., and thus were irrelevant to agriculture (NOT AGRICULTURE).

Criterion 2: *the focus to agricultural policy evaluation subject*. We consider a paper to be relevant if the agricultural policy is a key component of the model that directly affects the model outcome and consequently the paper focuses on the relation of the policy to the model outcome. We included papers which attempted an ex-ante evaluation of a specific policy or evaluated at two or more alternative agricultural policies or different components of a single policy. Based on abstract inspection and on full text inspection when necessary, we removed 72 items and came down to 59 papers that were ABM for agricultural policy evaluation.

Criterion 3: the granularity of the agent. We identified two distinct categories, with different methodological issues. The first uses agents to represent individual farms and the second assigns them to aggregated entities, e.g. representative farms, regions, etc., or non-farm entities like landscape cells, animal or plant agents, etc. We selected to deal only with individual farm models. Based on full text inspection, we removed 8 papers.

Criterion 4: Regarding the questions that are addressed. We distinguish between data-driven models and theory-driven models, following Barlas (1996) and Polhill et al. (2013). Data-driven models focus on reproducing real world situations and thus are driven and validated by collected data and evidence. In the second category the models are based on qualitative information and second order data (stylized facts) and are used for exploring questions in principle, e.g. looking for emerging properties like resilience, etc. Ex-ante policy evaluation is pursued by means of farm models that simulate an actual farming system (Reidsma et al., 2018; Langrell et al., 2013). Due to the empirical policy orientation of the paper, we focus on data-driven ABM. We thus proceed with the data-driven (empirical) individual-farm ABM excluding 19 papers that were individual farm theory driven ABM policy evaluation papers.

An overview of the refinement process is in Fig. 2 and a detailed correspondence of criteria to publications, can be found in the excel supplement.

Thus we conclude to 32 empirical-based and individual-farm relevant papers published between 2000 and 2016 as in Table 1. In Fig. 3 we depict the temporal evolution of the various recognized categories. The agriculture-related ABMs (greens) are constantly increasing from 2005 and onwards and the same happens for agricultural policy evaluation ABMs (dark greens).

[1] Farm type models are originally built by means of mathematical programming, econometric modeling or simulation techniques. Due to suitability to investigate novel policy instruments (advantage over econometric models) and their time and cost efficiency (comparing with simulation models) mathematical programming in various forms (LP. NLP, MILP) prevailed to the others. When we mention throughout the text the term “traditional models” for agricultural policy analysis, we refer to the above three categories, most often though in MP models. On the other hand, combined econometric-mathematical programming models as well as ABMs or ABMs combined with mathematical programming modules are novel approaches still in the making.

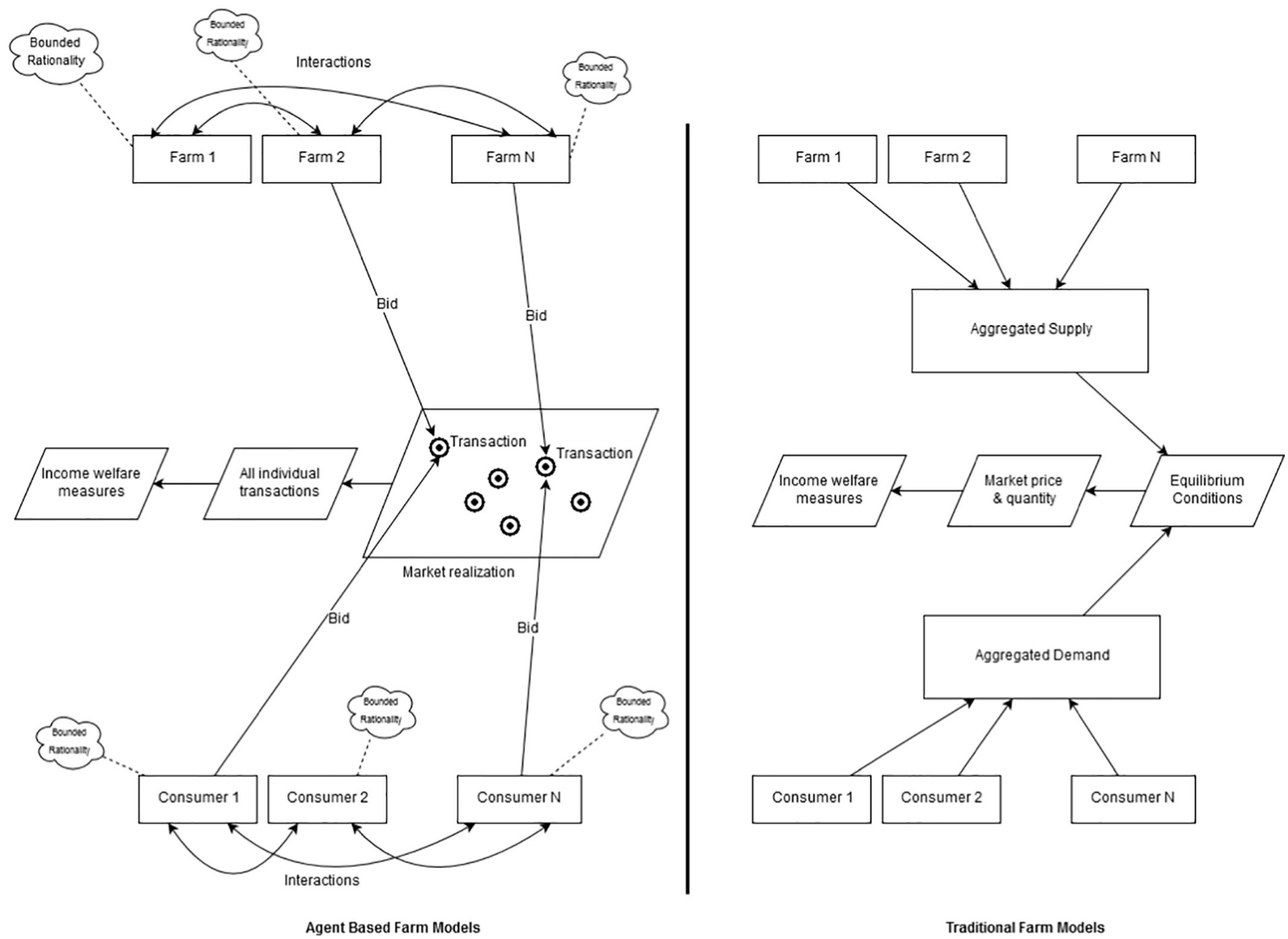

Fig. 1. Conceptual difference between Agent Based Modeling approach and traditional microeconomic farm models (adapted from Nolan et al., 2009).

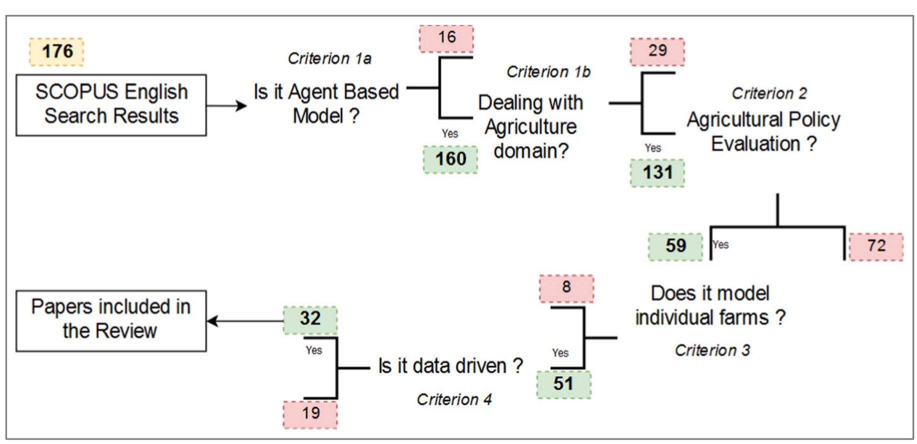

Fig. 2. Overview of search results filtering process.

2.3. Research questions

To define research questions in relation to the critical aspects of wider scientific community acceptance, we consider four ABM related review papers in the agricultural related fields (land use change, socio-environmental issues, etc.) published so far:

Parker et al. (2003) reviewed multi-agent systems for the simulation of land-use change. Regarding empirical modeling they conclude than ABMs greatest advantage and at the same time shortcoming is their flexibility of specification and design that calls for focusing on verification and validation procedures. Furthermore, among others, they recognize the following challenges: the consolidation of the different individual decision making approaches and the communication of the models.

Bousquet and Le Page (2004) reviewed the development of multi-agent systems for ecosystem management. They find that the greatest advantage of ABMs is the combination of their spatial nature and the ability to represent networks. Among others, they raise the questions of

Table 1
List of reviewed papers.

Authors	Year	Title	Source title	Short name
Berger T.	2001	Agent-based spatial models applied to agriculture: A simulation tool for technology diffusion, resource use changes and policy analysis	Agricultural Economics	Berger (2001)
Sengupta R., Lant C., Kraft S., Beaulieu J., Peterson W., Loftus T.	2005	Modeling enrollment in the Conservation Reserve Program by using agents within spatial decision support systems: An example from southern Illinois	Environment and Planning B: Planning and Design	Sengupta et al. (2005)
Happe K., Kellermann K., Balmann A.	2006	Agent-based analysis of agricultural policies: An illustration of the agricultural policy simulator AgriPolis, its adaptation and behavior	Ecology and Society	Happe et al. (2006)
Berger T., Schreinemachers P., Woelcke J.	2006	Multi-agent simulation for the targeting of development policies in less-favored areas	Agricultural Systems	Berger et al. (2006)
Schreinemachers P., Berger T., Aune J.B.	2007	Simulating soil fertility and poverty dynamics in Uganda: A bio-economic multi-agent systems approach	Ecological Economics	Schreinemachers et al. (2007)
Happe K., Balmann A., Kellermann K., Sahrbacher C.	2008	Does structure matter? The impact of switching the agricultural policy regime on farm structures	Journal of Economic Behavior and Organization	Happe et al. (2008)
Brady M., Kellermann K., Sahrbacher C., Jelinek L.	2009	Impacts of decoupled agricultural support on farm structure, biodiversity and landscape mosaic: Some EU results	Journal of Agricultural Economics	Brady et al. (2009)
Freeman T., Nolan J., Schoney R.	2009	An agent-based simulation model of structural change in Canadian prairie agriculture, 1960–2000	Canadian Journal of Agricultural Economics	Freeman et al. (2009)
Happe K., Schnicke H., Sahrbacher C., Kellermann K.	2009	Will they stay or will they go? simulating the dynamics of single-holder farms in a dualistic farm structure in Slovakia	Canadian Journal of Agricultural Economics	Happe et al. (2009)
Sahrbacher C., Jelinek L., Kellermann K., Medonos T.	2009	Past and future effects of the common agricultural policy in the Czech Republic	Post-Communist Economies	Sahrbacher et al. (2009)
Le Q.B., Park S.J., Vlek P.L.G.	2010	Land Use Dynamic Simulator (LUDAS): A multi-agent system model for simulating spatio-temporal dynamics of coupled human-landscape system. 2. Scenario-based application for impact assessment of land-use policies	Ecological Informatics	Le et al. (2010)
Gibon A., Sheeren D., Monteil C., Ladet S., Balent G.	2010	Modeling and simulating change in reforesting mountain landscapes using a social-ecological framework	Landscape Ecology	Gibon et al. (2010)
Lobianco A., Esposti R.	2010	The Regional Multi-Agent Simulator (RegMAS): An open-source spatially explicit model to assess the impact of agricultural policies	Computers and Electronics in Agriculture	Lobianco and Esposti (2010)
van der Straeten B., Buysse J., Nolte S., Lauwers L., Claeys D., van Huylenbroeck G.	2010	A multi-agent simulation model for spatial optimisation of manure allocation	Journal of Environmental Planning and Management	van der Straeten et al. (2010)
Roeder N., Lederbogen D., Trautner J., Bergamini A., Stofer S., Scheidegger C.	2010	The impact of changing agricultural policies on jointly used rough pastures in the Bavarian Pre-Alps: An economic and ecological scenario approach	Ecological Economics	Roeder et al. (2010)
Happe K., Hutchings N.J., Dalgaard T., Kellerman K.	2011	Modeling the interactions between regional farming structure, nitrogen losses and environmental regulation	Agricultural Systems	Happe et al. (2011)
Chen X., Lupi F., An L., Sheely R., Viña A., Liu J.	2012	Agent-based modeling of the effects of social norms on enrollment in payments for ecosystem services	Ecological Modeling	Chen et al. (2012)
Brady M., Sahrbacher C., Kellermann K., Happe K.	2012	An agent-based approach to modeling impacts of agricultural policy on land use, biodiversity and ecosystem services	Landscape Ecology	Brady et al. (2012)
Bakam I., Balana B.B., Matthews R.	2012	Cost-effectiveness analysis of policy instruments for greenhouse gas emission mitigation in the agricultural sector	Journal of Environmental Management	Bakam et al. (2012)
Nainggolan D., Termansen M., Fleskens L., Hubacek K., Reed M.S., de Vente J., Boix-Fayos C.	2012	What does the future hold for semi-arid Mediterranean agro-ecosystems? - Exploring cellular automata and agent-based trajectories of future land-use change	Applied Geography	Nainggolan et al. (2012)
Schouten M., Opdam P., Polman N., Westerhof E.	2013	Resilience-based governance in rural landscapes: Experiments with agri-environment schemes using a spatially explicit agent-based model	Land Use Policy	Schouten et al. (2013)
Huber R., Briner S., Peringer A., Lauber S., Seidl R., Widmer A., Gillet F., Buttler A., Le Q.B., Hirschi C.	2013	Modeling social-ecological feedback effects in the implementation of payments for environmental services in pasture-woodlands	Ecology and Society	Huber et al. (2013)
Widener M.J., Bar-Yam Y., Gros A., Metcalf S.S., Bar-Yam Y.	2013	Modeling policy and agricultural decisions in Afghanistan	GeoJournal	Widener et al. (2013)
Daloğlu I., Nassauer J.I., Riolo R., Scavia D.	2014	An integrated social and ecological modeling framework—impacts of agricultural conservation practices on water quality	Ecology and Society	Daloğlu et al. (2014)
Smajgl A., Xu J., Egan S., Yi Z.-F., Ward J., Su Y.	2015	Assessing the effectiveness of payments for ecosystem services fordiversifying rubber in Yunnan, China	Environmental Modeling and Software	Smajgl et al. (2015)
Wossen T., Berger T.	2015	Climate variability, food security and poverty: Agent-based assessment of policy options for farm households in Northern Ghana	Environmental Science and Policy	Wossen & Berger (2015)
Troost C., Walter T., Berger T.	2015	Climate, energy and environmental policies in agriculture: Simulating likely farmer responses in Southwest Germany	Land Use Policy	Troost et al. (2015)
Guillem E.E., Murray-Rust D., Robinson D.T., Barnes A., Rounsevell M.D.A.	2015	Modeling farmer decision-making to anticipate tradeoffs between provisioning ecosystem services and biodiversity	Agricultural Systems	Guillem et al. (2015)

(*continued on next page*)

Table 1 (*continued*)

Authors	Year	Title	Source title	Short name
Morgan F.J., Daigneault A.J.	2015	Estimating impacts of climate change policy on land use: An agent-based modeling approach	PLoS ONE	Morgan & Daigneault (2015)
Appel F., Ostermeyer-Wiethaup A., Balmann A.	2016	Effects of the German Renewable Energy Act on structural change in agriculture – The case of biogas	Utilities Policy	Appel et al. (2016)
Baillie S., Kaye-Blake W., Smale P., Dennis S.	2016	Simulation modeling to investigate nutrient loss mitigation practices	Agricultural Water Management	Baillie et al. (2016)
Wossen T., Berger T., Haile M.G., Troost C.	2016	Impacts of climate variability and food price volatility on household income and food security of farm households in East and West Africa	Agricultural Systems	Wossen et al. (2016)

whether individual decision making rules shall be based on theory or elicited from observation; and of the credibility of the model, i.e. the presentation of its structure and assumptions and their validity.

Matthews et al. (2007), list as distinct advantages of ABMs the ability to couple social and environmental models; the capacity to study the emergence of collective responses to environmental management policies; and the ability to model individual decision making entities incorporating the interactions among them. They find that the prime challenge of ABM is to show that they can provide new insights into complex natural resource systems and their management.

Kaye-Blake et al. (2009), provides a more technical overview of the various approaches of different existing models regarding the modeling of markets (land, water, labor, etc.); the incorporation of risk preferences and other personality traits in the agent decision making; and the issues of information transfer and opinion transfer between agents.

Based on the advantages and challenges listed by the aforementioned review papers, and also on the requirements of farm-level models sketched by Berger and Troost (2014) mentioned already in the introduction, we shaped the following research questions (RQ):

RQ1: What is the status of the published corpus regarding model transparency? Transparency is crucial for empirical policy modeling. End users of ABM shall be able to easily identify the assumptions, relationships, and data used in a model. Since ABMs are loosely implemented in software, even when object oriented paradigm is adopted, transparency is a difficult issue to tackle with and thus we classify the reviewed papers in order to provide an overall evaluation of the transparency status. Furthermore, this is a longstanding problem that the ABM community has recognized, e.g. see the OpenABM computational model library in https://www.comses.net.

RQ2: What is the approach of the published papers regarding the modeling of agent behavior? In past review papers the ABMs flexibility to model individual behavior is considered a major advantage and in Reidsma et al. (2018) ABMs are found to be promising for modeling farmer interactions and farm structural change. However the high degree of modeling freedom results in a loose family of models very diverse between them and difficult to compare, reuse and summarize. Thus we attempt a structured classification of the various behavior modeling approaches, in order to identify potential strengths and weaknesses.

RQ3: What methods are used for initializing agent population? Agricultural policy ABM is used so as to represent an existing farming system in fine-grain detail, e.g. in plot level or/and farm population level of a certain area. However, available datasets are usually not sufficient due to aggregated or incomplete data. Consequently it is necessary to initialize/synthesize the farm population and allocate it in space. The validity of the initial virtual population has important implications for the validity of the model itself, since any significant diversion of the properties of the virtual population from the real one renders the model results disputable.

There are also other important challenges that we do not examine here, mainly because they are of a more general farm modeling interest and discussing them would require significant space and would rather distract the focus from empirical ABM. However, we understand to be important and thus provide key references that came up during the review process: *the model's process validity*, where the papers of Robinson et al. (2007) and the book edited by Smajgl and Barreteau (2014) highlight how to use empirical methods to accurately represent human behavior; *how to deal with model uncertainty*, where Troost (2014) use a systematic approach based on Design of Experiments (DOE); Parry et al. (2013) uses a Bayesian sensitivity analysis approach; and Ligmann-Zielinska et al. (2014) propose a simulation framework based on quantitative uncertainty and sensitivity analyses to build parsimonious ABMs.

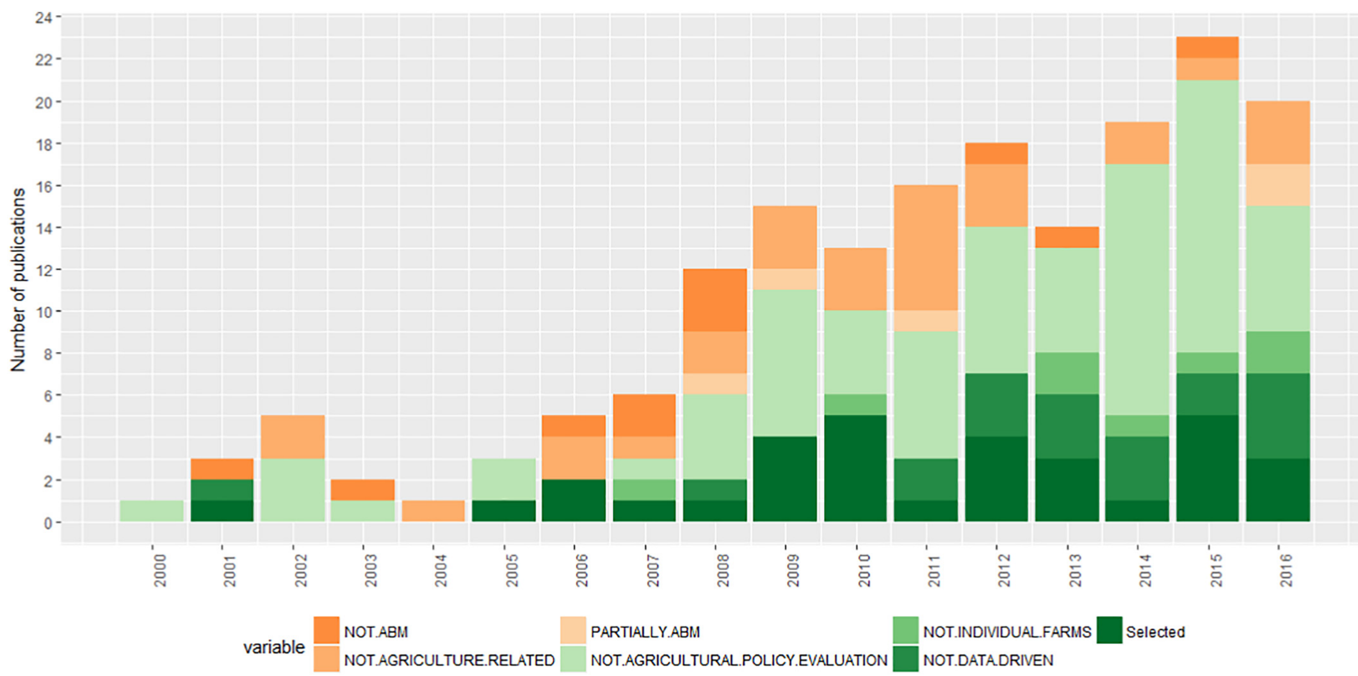

Fig. 3. Temporal distribution of search filtering process.(For interpretation of the references to color in this figure the reader is referred to the web version of this article.)

Table 2
Data extraction form.

	Data extracted		Comments
RQ1 (Model transparency)	1.1	Does the paper follow the well-established Overview, Design concepts, Details (ODD, Grimm et al., 2010) documentation protocol and/or its extension ODD + D (Müller et al., 2013)?	An indicator of the documentation quality
	1.2	What is the level of the results' reproducibility?	In detail: (a) Is executable or source code available? (b) Is a source dataset available?
	1.3	Does the paper explicitly report the simulation verification process?	How the modeler ascertains that the model is credibly coded and run in the simulator
RQ2 (Agent behavior)	2.1 to 2.29	We adjusted the *Overview, Design concepts, Details + human Decision making* (ODD + D) of Müller et al. (2013) so as to categorize the reviewed papers on several aspects of agents' decision making. More specifically, we took the ODD + D *Design concepts* section and converted most of the guiding questions to classification questions.	The agent behavior aspects include: Individual Decision Making, Learning, Individual Sensing, Individual Prediction, Interaction, Collectives, Heterogeneity, Stochasticity and Observation. See the Appendix A for a detailed description of the 29 elementary data extracted
RQ3 (Population synthesis)	3.1	What is the data source used to create the initial population?	
	3.2	What is the method to create the initial population?	
	3.3	What is the method to position agents in space?	

2.4. Data extraction and synthesis

In order to address the research questions, we read the full texts of the 32 primary studies and used a data extraction form to record our findings. The data extraction form is given in Table 2 while the extracted data can be found in detail in the excel file in the supplementary material.

An important note regarding the data extraction process is that we abstain from concluding that a certain property or feature is not existent in a paper. Due to the complex model structure (for almost half of the papers we had to consider an additional source like another paper or a manual) ABMs most often have, it is possible that a feature was not stated clearly or not reported at all; thus a Type II error (false negative) is probable.

Finally we followed up with a synthesis by collating and summarizing the extracted data in a manner that is suitable to answer our research questions. We employed descriptive and qualitative analysis on our data, while statistical meta-analysis was not possible due to the Type II error and the relatively small number of observations.

3. Results and discussion

3.1. Literature consolidation

More than 65% of the papers mention that they use a modeling framework.[2] Agripolis is used in eight papers while MP-MAS in six, while the rest used by one paper are Aporia, ALUAM-AB, ARLUNZ, CORMAS, LUDAS, RegMAS, RF-MAS, ERA. Regarding modeling toolkits, RepastJ or Repast Simphony is used in three papers, while Netlogo in two.

Land use change and *environmental impact assessment* is within the

[2] "A modeling framework is a collection of building blocks (i.e., coded methods) and a generic system structure (i.e., abstract classes representing actors in the system, how they can interact and behave, as well as scheduling actions) that enable researchers to focus on conceptual representations of the study system; justification of model parameterization; and calibration rather than developing a model from scratch. Frameworks are significantly more refined than general ABM toolkits, as they integrate domain knowledge and preassemble building blocks that facilitate domain-specific research questions (e.g., land-use change, production decisions)". (Murray-Rust et al., 2014)

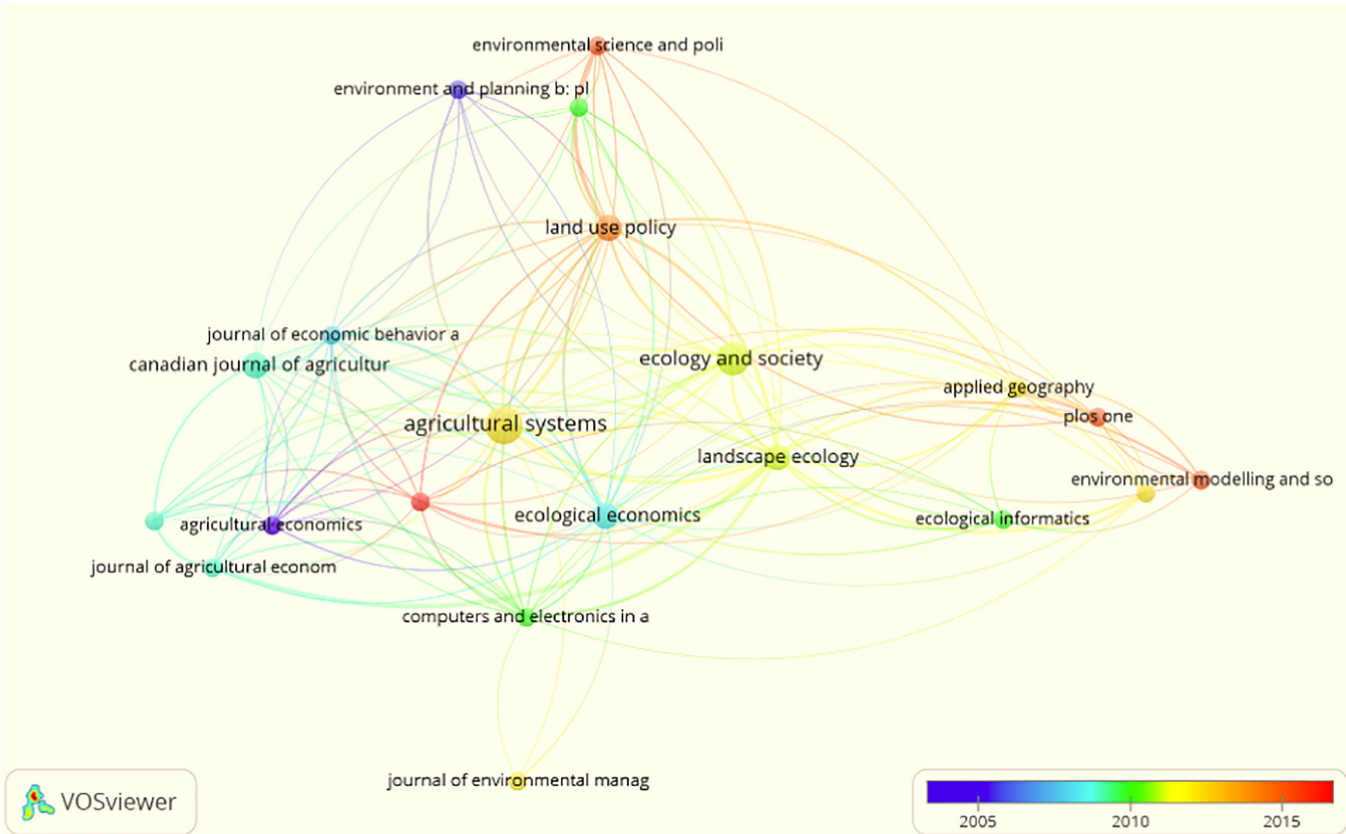

Fig. 4. Network of journals using bibliographic coupling analysis in VOSviewer. The positioning of items is determined based on the number of references they share; edges between two nodes denote that there is at least one common reference between them. Two source journals are omitted from the graph as outliers to optimize visibility: Agricultural Water Management that is only linked to Land Use Policy and Geojournal not linked to any other journal. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

subject of about one third of the papers while *structural change* and *income, production or market projections* of one quarter of the papers. On average, the study area is approximately 1000 km2, including around 1600 agents with a time span of 20 years.

The journal with the most reviewed publications is *Agricultural Systems*, an indicator of the multi-disciplinary nature of the ABM approach. Also many papers are published in journals directly related to environmental management and some to journals related to geography, another indicator of the spatial nature of ABM.

In Fig. 4, Agricultural economics (Ag.Econ) journals appear in deep and marine blue that is prior to 2010 and they are located mainly in the south west quartile of the map, which means that they cite similar references, in other words they drill from the same sources. Policy, systems and environmental analysis journals appear after 2010, they cite both Ag.Econ (the seminal papers) and others. A possible explanation is that first publications concern the methodology and theory so they fulfilled requirements of Ag.Econ journals whereas the latter ones focus on implementing the methodology with emphasis in the environment. Another explanation could be that after succeeding to the rigorous scrutiny of Ag.Econ journals, teams who developed such ABMs were solicited in research projects undertaken by multidisciplinary consortia. The output of these projects had a broader scope beyond disciplinary journals in agricultural economics, notwithstanding higher impact factors.

3.2. Model transparency

Over 60% of the reviewed papers followed the ODD or the ODD + D (Müller et al., 2013) documentation protocol. This clearly enhances the readability of the models by other researchers. But still, since ODD is originally targeting ecology ABMs, the ODD + D (Müller et al., 2013) seems a promising extension that covers several human decision making aspects and it should be more widely adopted.

Another effort toward improving documentation quality is to prototype the creation process of the empirically based ABMs itself. The paper of Smajgl et al. (2011) is moving toward this direction. They propose a parameterization procedure for empirical ABMs, composed by three steps: Extracting different agent classes and corresponding behaviors; eliciting each agent class behavior parameters or rules; and assigning each individual member of the simulation population to some kind of behavior. This framework can be potentially transformed to a documentation protocol, like ODD, with relevant questions common to all empirically based ABMs that will clarify to a great extent each model's approach.

On most papers (22 out of 32) of the reviewed papers we did not recognize any possibility of *reproducing the results*. In two papers the source code was available, in another two the source and the model's dataset was provided, and in another six the executable files and data was available to reproduce the results. Reproducibility provides credibility to empirical models and more attention shall be given by authors and by journals publishing related work. We believe that at minimum, an executable and a related dataset shall be available to model users.

Regarding *model verification*, for the models that provided source code, this is partially fulfilled since the end users can check themsevles the model verification, although practically this may not hold, e.g. the end user does not have command of the model's programming language. In any case, in two reviewed papers the verification process is explicitly stated to be performed by means of unit testing. *Unit tests* are a powerful tool for doing so: As Daloğlu et al. (2014) is describing, the software development is happening in small steps, and for each step

Table 3
Proposed verification stages.

Documentation	Level 1	Explanation of the simulation model by self-means (as discussed in Müller et al., 2014)
	Level 2	Follow a broadly recognized and well structured (initial conditions, timing, interaction, unit tests, exposition of the mechanics of the simulation) documentation procedure, e.g. ODD + D
Reproducibility	Level 3	Ability to reproduce the results (Take the simulation executable and run it with only one dataset and reach the same results)
	Level 4	Ability to change the assumptions of the simulation, run the model and test the sensitivity of the results (Source code is provided)

code test units are written that are fed with a predefined input followed by a comparison of the expected and observed output of the test unit. This testing process could also act as the public verification of the model when unit tests are given alongside with the executable.

Overall, we propose a four-level incremental scale to characterize the quality of model transparency: access to model documentation; following a documentation protocol; dataset and executable; dataset and source code (Table 3). In Fig. 5 we give an assessment of the model transparency quality of the reviewed papers.

3.3. Agent behavior

3.3.1. Results

Regarding the decision making entity (the agent), almost 70% of the papers refer to a *farmer/farm* where the decision making (DM) process is revolved around production or/and investment while the rest to a *farm household* where DM also includes consumption. Other DM objects found, although less frequent, regard the land use or a conversion to a management practice.

We did not notice papers to include agents in lower or higher scales. By *agents* we mean entities that display autonomous and proactive agency in contrast to passive entities, e.g. "agents" that serve as database for other real agents to retrieve info from. This latter type of so-called agency is present in many papers, but since it is a merely technical software construct, it does not affect the dynamics of the simulation and we are not interested on reviewing and reporting on this. In the existing literature, decision making was studied only in a single scale (that of the farmers agents), and the effects of decision making at different scales are largely unexplored.

Regarding the DM algorithm, about 60% of the reviewed papers are considering rational agents using *explicit mathematical programming optimization* (MP), about 20% employ reflective agents using *simple rules* (SR), e.g. if neighbor is in state A, then do B. The rest employ some type of *behavioral heuristics* (BH), e.g. calculate the utility of the alternatives and select the maximum. If we regard papers that use the same modeling framework as a single paper (it is plausible to do so, since a modeling framework uses the same DM approach across all related publications), then MP is used 45%, SR by 30% and BH by 25% of items.

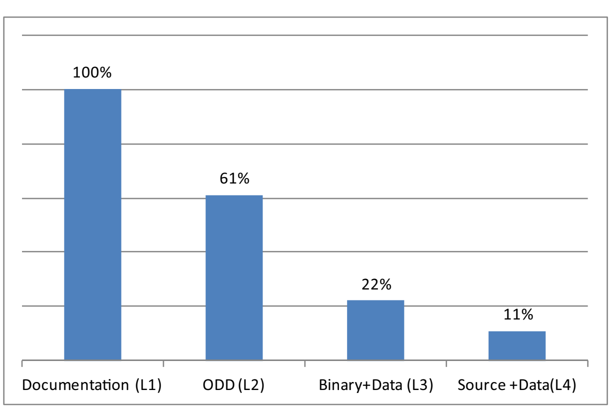

Fig. 5. Quality of model transparency.

In almost 20% of the papers the agent DM process is itself a stochastic process, e.g. the agent maps a probability of selection to the alternatives and the simulator select randomly using those probabilities. Also we did not notice any paper to explicitly consider the variability of any parameter of the DM algorithm, e.g. the variance of price is a parameter of the agent's decision model.

In over 85% of the papers the agents were adaptive. We considered an agent to be adaptive if he is capable of responding to other agents and/or its environment change of state; this is a very broad definition of adaptiveness where even simple reactiveness is included. On all papers that included adaptive agents, spatial aspects were incorporated in the DM (e.g. an agent is located in space and thus holds specific endowments). In almost 70% of the reviewed papers, temporal dimension was also affecting DM (e.g. data from past events or prospects of future outcomes). On the other hand we did not notice a paper that incorporated social norms or cultural values in DM.

We identified learning in two papers. By *learning* we mean the improvement of the agent's performance in the course of time by gaining more information/knowledge of the environment.

In 85% of the papers agents were sensing their environment and the nature of that sensing was rather global, e.g. all agents read a product global price; than local, e.g. read the neighbor's price (4 papers). We did not notice any paper to explicitly model the sensing process but rather information was directly provided to agents. We also did not notice any paper to model errors in sensing, e.g. stochastic sensing could serve as such, or costs for sensing.

In about half of the reviewed papers the agents make predictions, i.e. the estimation of future conditions the agents will experience, like the use of expected prices or yields; however if we group papers by modeling framework, only in one quarter of approaches agents make predictions. In three papers the projection to the future was endogenously modeled.

As far as agents interaction is concerned, we identified it in 60% of the reviewed papers. Over 70% of those was referring to a land market and the rest to some kind of information exchange through a network. Land market was primarily implemented as non-direct type of interaction, e.g. agents were submitting bids to a database and they were globally cleared, while information exchange in most cases were modeled as a direct agent to agent interaction.

In two papers we identified collectives, i.e. emerging aggregations of agents that affect individual agents. In all reviewed papers agents were heterogeneous regarding their state variables, e.g. resource endowments, but only in five, agents were exhibiting diverse behavior, e.g. different goals and thus a diversified DM process.

Regarding simulation stochasticity, in one paper a global parameter was itself a stochastic element that was updated in each simulation turn. In < 30% of the reviewed papers it was reported that many runs were performed to account for the randomness in simulation parameters. In some of those papers it was stated that "*multiple runs with different initial random seeds were performed*". However since for pseudo-number generators, the series of two different seeds are correlated, the correct way to perform multiple runs is to use a single seed across all runs, using the first n numbers for the first run, the second n numbers for the next run, etc.

Regarding the presentation of the results, in all papers aggregated results were shown. In 25% of the papers a distribution of an observation variable was also given and in almost 30% a GIS map was provided.

In Fig. 6, we provide a graphical overview of the above results that provide. In the horizontal axis is the specific dimension we examine (e.g. Adaptive agents in model?, DM with spatial aspects in model?, etc.) and in the bar we show the percentage of papers we have

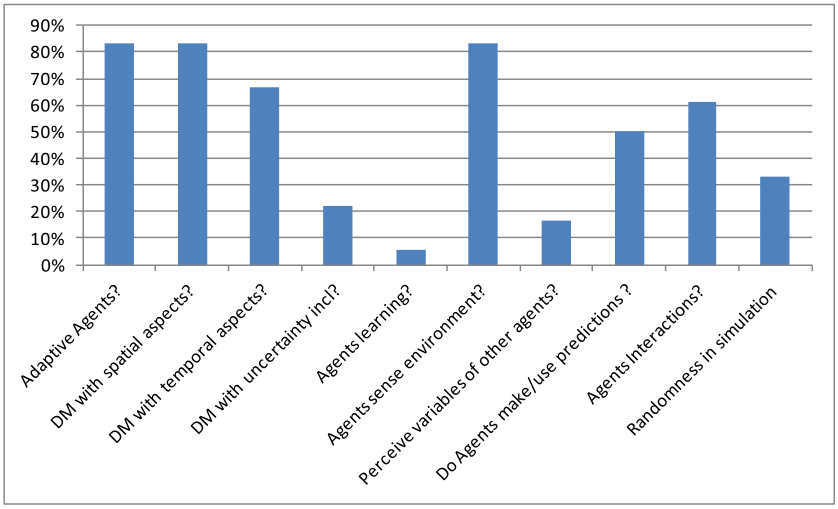

Fig. 6. Various aspects of agent decision making.

positively recognized to do so (e.g. in ~80% of papers we recognized to contain adaptive agents).

3.3.2. Discussion

Agents' reactiveness can be considered to be the minimum requirement for a model to be classified to the ABM discipline. From a modeling perspective, the agent's decision making algorithm shall contain a parameter, representing another agent's or an environmental stimulus, which potentially varies during the simulation. For more complex ABM settings, one or more of agents' sensing, interaction, prediction, learning and collectives shall be explicitly modeled. For the vast majority of the reviewed papers agents' reactiveness was easily identifiable, but the rest ABM elements, with the exception of interaction, do not seem to be frequently modeled.

We also find that emergent phenomena are not highlighted in the majority of the reviewed papers. By *emergent phenomena*, as Grimm and Railsback (2005) note, we consider output properties that are not simply the sum of the properties of the individuals and cannot easily be predicted by a priori consideration of the individual agents. For example the existence of path dependence on the distribution of farm sizes or a skewed distribution of the land uses can be considered emergent properties; they are properties of the system and not of the individual agents and cannot be derived by examining agents in isolation. ABMs are very suitable for highlighting emergent properties. The fact that most reviewed paper are not focusing on those properties can be attributed to their empirical orientation and that highlighting emergent phenomena might distract their scope. An exception is the paper of Happe et al. (2008) that examines the evolution of structural change in relation to different policy regimes. In any case, in the majority of the reviewed papers, we recognize spatial explicit models with heterogeneous agents' that nevertheless is a good argument to use the ABM approach, but we do not see the modeling of *complex adaptive systems* as discussed in Xepapadeas (2010).[3]

Thus a future research direction is to answer whether it is feasible that complex adaptive systems modeling, using ABMs, can provide useful insights for empirically based questions and another is how to do this credibly without increasing the model uncertainty and loosing focus from the policy question. One possible direction is to include more frequently currently overlooked elements (agents' sensing, prediction, learning and collective); another path may be the incorporation of heterodox theories on economic agent decision making, containing components on human bounded rationality, evolutionary decision making and interaction. For instance as discussed in Foley (1994), Day (2008) and Elsner (2012), could serve toward this end.

Regarding agent interaction, it is included in most of the reviewed papers and is modeled mostly in an indirect way (e.g. a third party clears the collected bids of all agents). We believe that more empirical research should be conducted for modeling explicitly the mechanisms and the parameters of the agent interactions. Good examples of empirical investigations about farmers' interaction are found in Mertens et al. (2016) and in Manson et al. (2016).

In a few papers, agents are interviewed about their reactions to various scenarios and then those are inserted in the ABM model. A promising extension of this approach is that of Delmotte et al. (2016). The farmers are iteratively providing decision choices through software that then feed the ABM model. A remote (e.g. web based) gamification framework, where farmers will participate in a *business game*, providing their decisions online, can potentially replace the one-shot interview that elicits agents attitudes.

Regarding the stochasticity of the models, most papers do not report how they deal with the randomness in the simulation. It is not mentioned explicitly that multiple runs were performed and furthermore result-variables are reported without statistical measures (mean, standard deviation, etc.). ABM may be considered as stochastic computer experiments, since agents' properties are usually random distributions (e.g. positioning of agents, multivariate distributions of agent properties, etc.); and also agents' interactions can be modeled only as stochastic processes, e.g. agents are randomly selecting another agent from a set of neighboring-agents to commit a transaction. Thus the stochastic nature of ABMs dictates that the results should be given in the form of appropriate statistical distribution parameters, something that is not common among reviewed papers. Furthermore advanced data analysis techniques, like time series analysis, spatiotemporal methods and data mining algorithms could be incorporated in ABM software packages as discussed and exhibited in Lee et al. (2015). Also we find very interesting, although not popular among the reviewed papers, the insertion of a stochastic element in the DM process. For empirical models, that could compensate for the lack of exact knowledge on agent behavior.

Overall, since there is homogeneity of the subject and the object of decision making, we believe that it is feasible to develop a unifying decision making and interaction framework. A common object oriented

[3] "Economic, social, and ecological systems are examples of Complex Adaptive Systems. Economic systems are comprised of individual agents that pursue their own objectives and interact among themselves. These interactions lead to the emergence of macro behaviors that ultimately may feed back to influence the actions of individual agents, but typically on different time and spatial scales. The actions of individual agents and the emerging macroscopic outcomes may also be influenced by actions taken by regulatory institutions in their attempt to mitigate externalities associated with individual actions."

programming framework would help toward this direction as Bell et al. (2015) propose. In fact *Aporia framework* (Murray-Rust et al., 2014) uses such an object-oriented approach for modeling the agent decision making for agricultural land use and may be a good step toward this end.

3.4. Population synthesis

Regarding the *data source used to create the initial population*, in 18 papers a microeconomic database was used, in 9 interviews with all or a sample of the agent population and in two papers GIS data was used. For 3 papers we could not identify the data source. We find that data scarcity is not a major barrier since detailed geographical data (e.g. cadastral maps, land use maps, etc.) and disaggregated data of farm surveys, are often used by the reviewed papers. Interviews may also prove cost effective when models deal with relatively small areas with a few agents.

Regarding *the method used to create the population*, in 8 papers *cloning* was used. By *cloning* we mean that a limited number of agents, less than the number of the simulation agents, were replicated in order to reach the final agent population. In eight papers a *monte carlo* method was used, where the agents' population is randomly drawn from an empirical joint distribution of the farm properties; the latter is created from the available data for a limited number of agents. Finally for three papers the agent population was a one-to-one correspondence of real data and for the rest 13 we could not identify how the initial population was created.

The problem with the cloning approach is that, it reduces the variability of the model data compared to real population, multiplying the sampling error and possibly affecting the validity of the model dynamics. Furthermore, no sensitivity analysis regarding the random effect of the population generation process can be conducted, since only one population can be generated, i.e. the clones of the sample farms. Monte Carlo methods, as discussed in Berger and Schreinemachers (2006) hold better statistical properties.

Regarding *the method used to position agents in space* in 12 papers we could not identify this method, in 18 papers it was randomly positioned and in two the plots of the farmers were corresponding to real data. Random positioning ignores the likely spatial autocorrelation of their properties but can be overlooked if the simulation is dealing with a spatially homogeneous farming system. Otherwise, provisions should be made to spatially allocate the agents based on at least some plausible evidence. In any case, spatial location can potentially be included in the population synthesis process; spatial location being a farm property. Mack et al. (2013) is closer to this approach.

From a software engineering point of view, incorporating population synthesis as a distinct module with a special user interface may provide to end users the ability to experiment on the impact of data downscaling assumptions to the model output.

Overall, regarding population synthesis and spatial allocation, there seems to be a rigorous research interest, not directly related to agricultural policy ABM, but with potentially applicable results to empirical models for agricultural policy evaluation. For instance the paper of Harland et al. (2012) reviews and compares three state-of-the-art spatial population generation techniques (deterministic reweighting, conditional probabilities and simulated annealing) and Hamada et al. (2015) present a novel kernel estimator for reconstructing an entire population from a small sample survey.

4. Conclusions

ABMs can complement conventional farm models for policy analysis, as pointed by Berger (2001): heterogeneity of behavior can easily be modeled; a wide range of farm to farm interaction can be included like information exchange, markets of locally available resources with endogenous price formation, etc.; dynamic comparative analysis can be undertaken as opposed to the comparative static approach of equilibrium based farm models; spatial element is inherently included and that allows to investigate the spatial dynamics of various properties, e.g. the land rents. Another key strength is the ability to link human and environmental elements using space as the common element, a very important feature considering the pro-environmental orientation of contemporary agricultural policy.

In this review we examined the ABM literature on policy evaluation from 2000 to 2016 in order to (a) consolidate it in a consistent and transparent way; (b) to examine the critical aspects of empirical based individual farm policy evaluation ABMs that will expand their use.

Regarding the literature status on policy evaluation ABMs, there is a significant increase in the number of publications after 2008 at a large extent due to the potential of early seminal papers published in the previous period. We distinguished between individual-farm ABMs and not-individual or non-farm ABMs, and between data-driven and theory-driven approaches. Fig. 3 provides an illustrative summary of their evolution. In this respect, researchers can carry over from the detailed literature classification, either for examining the groups of papers that we are not focusing into, or for a future review on the same subject.

We examined several critical aspects of empirical-based farm ABMs in relation to wider adaptation for policy analysis. Those aspects are based on past reviews and on generic farm model requirements sketched by Berger and Troost (2014). A summary of our findings is given below:

- *Modeling transparency*: We find that the majority of the papers follow the ODD protocol (Grimm et al., 2010), however the overall level of modeling transparency has potential to be further improved. At a minimum an executable and related data shall be available to end users. When for privacy or copyright reasons data cannot be shared it is advised to make available synthetic sample data together with the model. Last but not least, unit testing is a good practice to be employed for public model verification.
- *The sufficient detail of farm management and agronomic conditions and the heterogeneity in behavioral constraints and behaviors*: ABMs can be as analytic as the traditional microeconomic models regarding the details on those aspects. Moreover, they can incorporate behavioral parameters that other type of models cannot; Learning, collective structures, modeling complex adaptive systems. We propose that more rigorous research is needed primarily on whether incorporating those can provide useful insights for empirically based questions and how to do this without increasing the model uncertainty and loosing focus from the policy question.
- *Farm interaction and incorporation of spatial dimension*: ABMs exhibit those two features to a satisfactory degree. However, more work shall be done so that interactions are modeled in a direct way and established on empirical data. More information shall be provided on the population initialization that includes positioning in space and statistically sound methods shall be established for doing so; the above two additions will improve the spatial dimension.

Overall, although ABMs clearly outperform mainstream modeling approaches in certain aspects, they face difficulties to be widely adopted by modelers and applicable for large scale assessment. By means of literature review, the present work attempted to identify some of them and provide insights for enhancement which along with advances in computing and standardization of parameterization and calibration processes can spread their use by policy analysts and decision makers.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.03.010.

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