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A review of agent-based modeling for simulation of agricultural systems

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Abstract
In this manuscript global research trends are analyzed in agent-based modeling (ABM), which is applied to face the inherent complexity of agricultural systems. The search was carried out in Scopus, during the period 2009-2019, and the VOSviewer© software was used as a bibliometric tool. The results show that ABM is used under two approaches: research and policy evaluation, and in three thematic areas: systems and computation sciences, geography and ecology and environmental science. The purpose of this study is to investigate three types of phenomena: land-use changes, water management and agricultural policy evaluation. ABM has been shown to be useful for exploring and understanding the society-nature relationship of agricultural systems under an interdisciplinary and transdisciplinary approach, and for supporting decision-making processes via its application in a Latin American context, which for our purposes is still of utmost importance.

Keywords: agricultural complexity; agricultural systems modeling; adaptive complex systems.

Una revisión de modelación basada en agentes para la simulación de sistemas agropecuarios

Resumen
En este manuscrito se analizan las tendencias globales en investigación de la modelación basada en agentes -MBA- aplicada para abordar la complejidad inherente a los sistemas agropecuarios. Se emplea la búsqueda en Scopus, durante el período 2009-2019, y el software VOSviewer© como herramientas bibliométricas. Los resultados obtenidos muestran que MBA se aplica bajo los enfoques de investigación y de evaluación de política en tres áreas temáticas principales: ciencias de la computación y sistemas, geografía, y ciencias ambientales y ecología; y para estudiar esencialmente fenómenos de cambios en el uso de la tierra, gestión del agua y evaluación de políticas agrícolas. Aunque MBA ha demostrado ser una herramienta teórica útil para explorar y comprender la interrelación sociedad-naturaleza de los sistemas agropecuarios desde enfoques inter y transdisciplinarios, así como para soportar los procesos de toma de decisiones, su aplicación en el contexto latinoamericano es aún incipiente.

Palabras clave: complejidad agropecuaria; modelación de sistemas agropecuarios; sistemas complejos adaptativos.

1. Introduction

The paradigm of complexity refers to a diversity of elements, multiple energy types and climatic circumstances that come together to spontaneously form temporary spatial and functional structures on a macro level [1,2].

Agricultural production is a type of social organization, where individuals develop techniques and both adopt and adapt technology, in order to take advantage of ecological function. It has the ultimate purpose of producing a commodity or other service, which can then be directly used by the community and its members, and/or be traded. Consequently, agricultural systems are defined in terms of natural resources, the individual and collective context, the

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interests of the decision makers at different levels, and the diverse interactions between all persons involved in the process. At any particular moment in time, agricultural systems inherently have a concrete objective in mind, and this objective along with the aforementioned characteristics ultimately defines the system [3].

In order to viably maintain existing interactions between nature, society, and the marketplace, the productive systems of agricultural goods and services evolve and self-organize, adapting to the many uncertainties that may arise from economic, climatic, and political changes at any one time.

According to [4], a complex adaptive system (CAS) is composed of diverse and numerous autonomous components (called agents), and is selectively adjusted via a self-regulation technique involving various networks. Furthermore, a CAS is homeostatic and behaves as a sole-working unit, adjusting to changes in the environment. CAS can learn from experience by constructing attractors based on past experiences that facilitate their response and the decision-making process depending on the environment (p.22).

For this reason, diversity and the interactions and interdependence among the elements that compose and explain the functioning of agricultural systems, allows us to consider them as a CAS. As explained in [5], if we assume that these elements combine biophysical processes from the natural environment with the human decision-making process - involving heterogeneous and autonomous agents - in tandem with being capable of adapting and evolving in response to environment changes, emergent patterns of agricultural structure may result in such a way that the analysis of agricultural systems cannot simply be reduced to productivity and conservation of physical means, but must also include the social environment in which these systems occur [6]. For this reason, collaboration between natural, social, and economic sciences, is not only desirable, but necessary in order to overcome agricultural difficulties.

Whilst modeling techniques have become useful tools and practices for representing, describing, explaining, predicting and/or evaluating the reality of changes in agricultural systems, other diverse means of investigation typically employ traditional mathematical models which emulate the problem with a mere technical question, from the point of just one discipline. Even when various factors are integrated, techniques based on classic logic are employed, which is reductionist, mechanist, and linear [1,6-9].

Consequently, the lack of available data and the limitations of experiments involving the socioeconomic aspects of agricultural systems make certain properties and behaviors unexplainable utilizing traditional methods [2].

Treating agricultural systems as a CAS therefore demands an approach that reflects the real characteristics of the phenomena in question, in addition to being able to connect micro behaviors with the agents' interactive patterns and guidelines of global behavior. This means that tools which consider any emerging phenomena that arise as context dependent are required. In short, to articulate this idea, there are no pre-established equations that allow us to explain agricultural systems, being composed of heterogeneous agents and not by "representative agents", as classical logic alleges, and various social processes can occur simultaneously in time and space [10].

Reality is not linear, therefore there is no proportionality among the entrances and exits of the system, and what is valid in one moment in a determined space, could be the opposite in another. Therefore, forces which are beyond the limits and reach of agricultural workers (investment of time, money and soil) do not necessarily mean better quality or quantity of production, nor does it mean a greater return in financial terms, or improved quality of life.

In this sense, [11] claim that day by day there is increasing consensus among model developers about the need for their simulations and models to contain a balanced representation of the economic, environmental, and social dimensions of any given system. In the same way, [4] show that interdisciplinary work is vital for the analysis of the CASs, in much the same way as the use of developed tools under the methodological framework of complex sciences, as with Agent Based Modeling (ABM).

ABM supplies a theoretical tool for modeling CASs. It is made up of interactive and autonomous agents, an environment, and a description of the interactions between agents and the environment, via rules of behavior and mechanisms of decision-making [12,13].

ABM is known for using natural language that facilitates the explanation of the dynamics of a system. It is flexible, links the micro (individuals) with the macro (structures or patterns) and does not require prior knowledge of added patterns, which means that it can perceive natural emergent phenomena, simulate temporality, space, and heterogeneity of the agents (behaviors, identities, preferences, etc.), can construct models of rationality and limited information, and conduct virtual experiments [14,15].

For this reason, the focus of ABM seems to be reasonably pertinent for representing, simulating, and analyzing the complexity of agricultural systems [5,16].

Recent reviews of the literature have analyzed the implementation of ABM in the agricultural context, but have stipulated a specific focus point of investigation as the place to start, as is the case with [17], which limited the analysis to the political side of agriculture. Nonetheless, in the present manuscript technical-scientific tendencies of the application of ABM to agricultural systems are examined in the period 2009 to 2019, with the purpose of establishing points of focus, important themes of discussion, the main fields of investigation and application, and to identify tools adjusted to ABM that integrate natural, social and economic sciences.

A bibliographic review was carried out, using the specialized database Scopus. The information was processed in two phases: 1) inventory of documents that were used in VOSviewer© and 2) classification of information to identify the tendencies of the areas of focus. Afterwards, the articles from the study which dealt with the use of ABM to analyze a specific agricultural system, were reviewed in depth.

The information analysis and posterior reflection evaluates current investigative tendencies and the applicability of ABM in integrating the diverse number of factors and interactions that make up an agricultural production system. Furthermore, it serves as a base to identify shortcomings, holes in logic, and other gaps to help the agricultural community in its decision-making.

2. Methodology

The questions that directed the investigation were as follows: Which models, platforms, or software have been designed based on ABM, to explain phenomena that occur in agricultural systems? Which methods, tools or techniques have been adjusted to ABM to analyze agricultural systems? How are social, economic, and environmental aspects of agricultural systems integrated into ABM? And finally, Is ABM an adequate tool for simulating the complexity of agricultural productive systems?

With the goal of analyzing the historical tendencies, a search was first done from the period 2000-2020 in the specialized database Scopus, employing the key words: “Agent based Model*” AND agricul* AND system. As a result, a total of 301 documents were obtained.

As was observed starting in 2009, the quantity of publications doubled with respect to previous years. Subsequently, the search was limited, starting from 2009, through to 2019. Results from the areas Medicine, Immunology and Microbiology, Chemical Engineering, Neuroscience, Materials Science, Physics and Energy, Biochemistry, Genetics and Molecular Biology were excluded, resulting in a total of 228 documents.

Finally, the route of search was: TITLE-ABS-KEY ("Agent based Model*" AND agricul* AND system) AND PUBYEAR > 2008 AND PUBYEAR < 2020 AND (EXCLUDE (SUBJAREA, "BIOC") OR EXCLUDE (SUBJAREA, "ENER") OR EXCLUDE (SUBJAREA, "MEDI") OR EXCLUDE (SUBJAREA, "CENG") OR EXCLUDE (SUBJAREA,"IMMU") OR EXCLUDE (SUBJAREA, "MATE") OR EXCLUDE (SUBJAREA, "NEUR")).

In order to be able to answer the research questions, the information processing was carried out in two phases, as described below.

Phase 1: Information processing was carried out in VOSviewer© a free software for bibliographic analysis, and was conducted in the following manner: 1) the information from the resulting 228 documents was downloaded in CSV format. 2) The downloaded file was imported into VOSviewer© in order to create a map based on the bibliographic data, via co-authorship (name of the authors, the organizations, the countries), co-occurrence of the keywords and source citation. 3) Since author names, organization names, country names, source names, and key words may have variants, for example agent-based model y agent based model, a Thesaurus [18] was created to gather the different variants in one sole term. 4) The graphic results were then analyzed.

Phase 2: To classify the information in order to identify the tendencies of the areas of focus and fields of application, the following steps were completed: 1) The search results in Scopus were organized in descending manner, in agreeance with the number of citations. This criterion was implemented as a bibliometric indicator of impact, according to [19]. 2) The abstracts of the 100 most cited articles were reviewed, and the information from each one (original title, reason for investigation, field of application, and other techniques incorporated into ABM) were imported into an Excel spreadsheet, filters were defined, and dynamic tables were created to calculate statistics. 3) Utilizing the description of the employed ABM as a selective criterion - it had to be sufficiently developed to be functional - 64 documents were selected. 4) 26 documents were chosen to complete a full literature analysis with the end goal of responding to the aforementioned questions.

3. Results and discussion

Below the results of Phase 1 are described, i.e., the analysis of the 268 documents identified from the search strategy previously described. Afterwards, the results of phase 2 are presented, which deal with the revision of the 100 most cited articles. Lastly, the analysis of the 26 full literature readings is discussed.

3.1 Phase 1: Bibliometric maps using VOSviewer©

Upon completing analysis of the scientific production per country, it was observed that the majority of publications come from the United States (29), Germany (19), France (18), and United Kingdom (14). Nonetheless, crosschecking that information with the quantity of citations, the countries with the greatest force, according to the total force as estimated by VOSviewer© are Germany (12), United Kingdom (10), and Denmark (9). 34% of the documents were published in the journals: Environmental Modelling and Software, System Approach, Ecological Economics y Ecological Modelling.

Co-authorship: 5 was defined as the minimum number of documents of a particular author without considering the number of citations per author. The top 3 investigators that publish the most about the topic in questions are: Berger Thomas.; Troost Christian & Topping Christopher John.

Berger T. and Troost C. belong to the University of Hohenheim in Germany, and they tend to co-publish, their emphasis being principally the use of ABMs as applied to risk management in agriculture, to be able to propose adaptive strategies. Their work is engaging and intriguing, as many of their studies have taken place in South America (Chile and the Amazon) and include socio-economic and biophysical integration.

Exploring more about these two authors on the platform Mendeley, it was discovered that Burger has an impact factor of 24 with 1,834 citations. The vast majority of his publications are in journals such as: Agricultural Economics, Agricultural Systems, Ecological Economics, Land Use Policy, and Environmental Modelling and Software. The impact factor for Troost is 7, with approximately 178 citations. In addition, they have a co-authorship of 14 publications, the majority corresponding to conference proceedings for events such as: Meeting of the International Environmental Modelling and Software Society, and articles in Agricultural Economics and Agricultural systems.

Furthermore, Topping C.J. belongs to the University of Aarhus in Denmark. His main area of work is the modeling of the ecological aspects of agricultural systems, specifically the behavior of animal populations, for which he has employed the ABM in addition to other techniques. His impact index is 24, with a total of 1,834 citations, according to the report given by the information provider Mendeley. The vast majority of these publications are in the field of ecology, such as: Ecological Modelling, BMC ecology, Ecotoxicology, Environmental Toxicology and Chemistry, among others.

From the co-occurrence of keywords: with a minimum of 5 occurrences and a total of 2.219 keywords, VOSviewer© initially defined that 160 keywords fit into the framework, nonetheless, it was necessary to include a Thesaurus document, and with this, the number of keywords was reduced to 86. For each keyword, VOSviewer© calculated the total force of the links of coincidence in the texts with other keywords, and grouped them into 4 clusters, as represented by the different colors in Fig. 1. The size of the framework reflects the weight of the keywords and the color shows the thematic group that each word belongs to.

28 elements belong to the white cluster, among which the keywords: land use (79), system approach (76), decision making (65), ecological analysis (53) are of particular prominence. 28 elements belong to the light gray cluster, among which the keywords agent- based model (161), agricultural analysis (109), simulation (97), computational methods (91), autonomous agents (53) and natural resources management (43) stand out. 19 elements belong to the dark gray cluster, among which the keywords environmental issues (51), sustainability (18) and environmental policy (10) are highlighted. Finally, the darkest gray cluster, is composed of 16 remaining items, among which the keywords economic analysis (56), agricultural production (31), GIS (16), nature-society relation (12) and decision support system (12) are of particular importance.

3.2 Phase 2: Identification of thematic areas and points of focus

Two important points of focus emerged from the information analysis, in agreeance with their orientation: from investigation (54%) and from evaluation of policies (41%). The former refers to analysis of the processes that occur in systems, while the latter focuses on practical questions regarding extension or regulatory policies, and how these affect the functional relationships of agricultural systems. The remaining 5% corresponded to revisions and reviews of associated literature.

Once the literature was grouped according to the emphasis of the publications, 3 thematic areas were identified: 1) Computer sciences. 2) Geography. 3). Environmental and ecological sciences.

Computer science: The use of ABM to obtain a general idea of the phenomena of the agricultural systems is inherent to the conceptual and methodological framework of the vision of the systems. In addition to the synergy of interests among model constructors and experts from other areas, to stimulate the behavior of agricultural systems. This has generated interdisciplinary investigations focused on providing efficient systems that give technical support to the process of decision making.

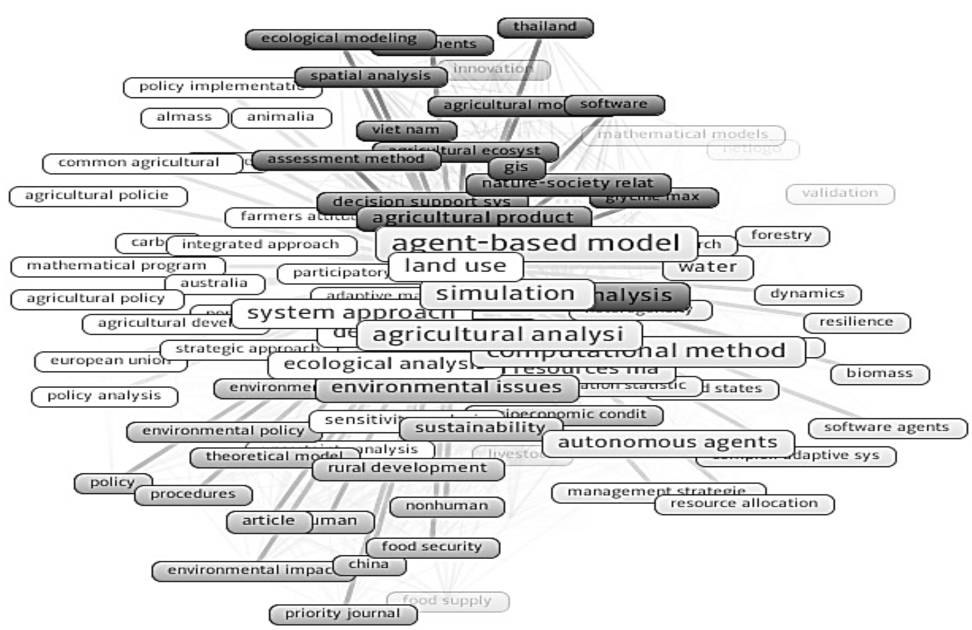

Figure 1. Bibliometric map of co-occurrence of keywords
Source: The authors in VOSviewer©

Geography: This refers principally to the links between human and environmental elements through the space in question, strongly developed via models of land use, that not only obey uses for the implementation of crops, but also changes in the landscape that could affect agricultural activity. For example, the development of road infrastructure or irrigation systems.

Environmental and ecological sciences: The different dynamics of ecosystems are studied, in particular those of animal populations (ants, spiders, wolves, beetles, etc.) and their interactions within the landscape. This includes, but is not limited to the simulation of invasive species, their reproduction and control.

The majority of the reviewed documents deal with issues that have been discussed by various disciplines, and therefore, one single document can belong to two or more thematic areas. This was also highlighted by [17] specifically for rules and regulations of agricultural evaluation.

The main agricultural phenomena studied with the ABM are land use, water management, and evaluation of agricultural norms and standards.

Land use: This conceptual category refers to the study of the interactions between ecosystems and human beings, and how this relationship affects global climate patterns that generate changes in economic and demographic factors that influence human behavior and the transformation of the natural environment to a constructed environment, whilst abiding by the objectives of agricultural production [20].

The application of this subsequent theory is connected to the search for the most productive and profitable crops and their distribution in small scale farms according to their characteristics, fertility, soil conservation, climatic effects, and rivalry of non-agricultural use; principally urbanization. All with the end goal of being able to support the decision-making processes in terms of sustainable agricultural practices.

Water management is associated with the intensive use of water for agricultural production, irrigation systems, and the scarcity thereof during times of drought, in such a way that guarantees ecological sustainability, and the food security of agricultural workers. In this way, the decision-making processes are supported in an informed manner, so to avoid conflicts and resulting negative practices related to water resources.

Evaluation of standards and norms is a developing work area, mainly in what is referred to as the evaluation of social, economic and environmental impact, before and after, and concerning the system to which the rules and regulations are applied, not to forget the practices by which the agents must abide.

In regard to changes in land use and water management, it was identified that the majority of these investigations are linked to the generation and evaluation of adaptive strategies of variability and climate change, causing therein a surge in the number of simulations directed towards the proposal of mitigation strategies. Within these simulations, different scenarios are created and sensibility analysis is carried out in order to support to the decision-making processes.

The aforementioned results are in accordance with [21] and [22], which point to the management of natural resources such as water and soil, in which ABM has most been applied, while for the case of the evaluation of agricultural rules and standards, evidence was found in [17].

3.3 ABM and the adjusted techniques used to study the complexity of agricultural systems

With each passing day, it is of greater interest to employ ABM as an integrative tool, which considers different economic, social and environmental dimensions in the analysis of agricultural systems. This has led to the modeling technique being applied to traditional modeling in areas such as ecology, the study of water, geography, economy, psychology, and archeology, among others, as well as to non-linear techniques such as system dynamics, network analysis, artificial neuron networks, and Bayesian networks.

Geographic Information Systems (GIS) is the tool that was found to be most aligned with ABM, giving place to spatially explicit models. Its purpose is to incorporate the physical environment and integrate it with the rest of the factors that make up agricultural systems, and in that way represent, simulate, and explore different space-time dynamics, identify land use patterns, and conduct sensibility analysis.

The majority of the models reviewed include the mathematical model of cellular automata and tools to represent space and the effect of proximity.

In addition, the models reviewed conceive the role of agriculture workers as active agents that autonomously make decisions about the management practices utilized, in terms of changes in the natural environment, and how to face changes that are out of their control (economic uncertainty, climate change, new rules and regulations), with the end goal of guaranteeing the multifunctionality of their system. Some of the investigations that integrate behavioral aspects of the agents use heuristic rules to handle the decision-making process with regard to the agricultural system, while others may incorporate the use of maps or cognitive cartography.

Although some academically renowned, pioneer, model proposals fall outside of the original search period (2000-2019), some initiatives are highlighted by [23], which proposes an evaluation framework for innovative processes and a change in the use of natural resources. Additionally, these initiatives use cellular automata and ABM to integrate economic submarkets in a spatial framework in tandem with the decision-making process on a home agricultural scale, in a region in Chile.

The Agripolis model, seeks to simulate and study the interrelationships between a large number of individually acting farms, product markets, investment activities, as well as the land market and a simple spatial representation [16].

In the area of land use change, the following were identified: the simulator of land use dynamics -LUDAS- applied in Vietnam [24,25], the interactive model based on agents for land use transition -ILUTABM- in the US [26], the Pampa model [27] and its extension on the land rental market -LARMA- [5] in Argentina, and the dynamic land use change tool CHANOS [28] in the Philippines.

Among the models developed to analyze water management were: multi-agent simulation of highly intertwined processes -MAELIA- applied in France [29-31], the virtual laboratory to explore the impact of climate change -SimKat- applied in Australia [32] and the interactive FlowLogo model [33].

Tools for the evaluation of agricultural policy have been designed such as: the participatory integrated evaluation framework of the agricultural system - PIAAS - [22], the model of nutrient emission based on livestock agents -ANEM- [34], and the regional simulator multi-agent -RegMAS- [35]. A more in-depth review specifically in this area can be found in [17].

The following models were found that specifically address the ecological component of agricultural systems: The multi-agent spatialized system for landscape colonization by Ash -SMASH- in the French Pyrenees [36], the Brown Plant Hoppers simulator -BPHSim- in Vietnam [37], the animal, landscape and human simulation system -ALMaSS- in Denmark [38] and the spatially explicit individual-based model for a wolf population -IBSE- in the southern region of Lake Superior in the USA and Canada [39].

Among the models that are outside the thematic areas indicated, but that nevertheless address problems present in agricultural production systems are: the agent-based life cycle analysis model for the potential adoption of switchgrass as biomass by farmers -AB-LCA- in the USA [40]; the Australian Animal Disease (Foot and Mouth Disease) Model -AADIS- [41] and the use of the multi-method simulation tool, AnyLogic®, which integrates the modeling of discrete events, of agent-based and system dynamics, to directly find optimal biomass storage in the US [42].

The most widely used agent-based simulation platforms for the analysis of agricultural systems are Repast, Netlogo, CORMAS and GAMA, and possibly as discussed, these additional tools have recently created environments that can be adapted according to interest. Furthermore, with the exception of CORMAS, these are open-source software.

Repast is a resourceful agent simulation toolkit created by the University of Chicago and the Argonne National Laboratory. Although it focuses on simulating social systems, it has been used to model evolutionary systems, market models and industrial analysis [43].

Netlogo is a modeling language and an integrated development environment for building an ABM. It was developed by Uri Wilensky, from Northwestern University, allowing the exploration of emerging phenomena and has a library of models that include a variety of disciplines such as economics, biology, physics, chemistry, psychology and systems dynamics. Due to the ease of its language, it can be used by both beginners, scientists and researchers [12].

CORMAS -Common-pool Resources and Multi-Agent Simulations- is a simulation platform developed by the Center for International Cooperation in Agronomic Research for Development (CIRAD), for the integrated management of renewable natural resources through the modeling of relations between societies and their environment [44]. It has a library of pre-established models that can be adapted and implemented to other contexts.

GAMA consists of a complete generic environment ready to simulate and model spatially explicit multi-agent systems, linking human and environmental elements across space. It uses RepastJ for the interface, OpenMap to support GIS, and GAML (based on XML) as a modeling language. It has been applied to simulate the spread of avian influenza in Vietnam and to reimplement, at a multi-scale level, the SAMBA model that was initially developed in CORMAS to simulate multiple agents at the micro level and to better understand individual decision-making and its consequences on agricultural dynamics and changes to land use [45-47].

The literature reviewed accounts for the interdisciplinary nature of ABM and its ability to analyze agricultural systems such as CAS, which evidences the diversity of relationships that emerge between crops, ecosystems, and the socio-cultural and economic aspects of agricultural production. Therefore, ABM is a useful theoretical tool in analyzing the inherent complexity of agricultural systems, representing the particular reality of each one, modeling them quantitatively, understanding them in a natural way and at different scales, and supporting the decision-making processes that occur.

One of the greatest challenges facing modeling of the complexity of agricultural systems, is that despite recognition of their dynamic nature, explained by human-induced changes and those that occur naturally, the lack of temporarily frequent empirical data, has led to the predominant simulations being static in nature, limiting their ability to model the learning and self-organization typical of CAS adaptation processes.

Regarding the application of ABM to agricultural systems in Latin American contexts, the modeling and analysis of land use and water management in Chile stands out. Some progress has been made in the region with investigations carried out with the support of European institutions, however they are still incipient. This leaves a window of job opportunities open for agricultural research institutions in Latin America to address additional issues, contexts and production systems.

4. Conclusions

This review has shown that the application of ABM to the agricultural field at a global level is recent and has increased since 2009. This increase has mainly been driven by the need to integrate social, economic, technical and environmental aspects in the sustainable management of natural resources, particularly water and land, for the production of agricultural food.

The complementarity between social and natural sciences has led to the formulation of widely used models, such as LUDAS, CHANOS, Agripolis, among others. Platforms such as CORMAS and environments for agricultural issues within Repast, Netlogo and GAMA has been developed based on ABM for supporting decision-making processes and agricultural policy evaluation.

Hence, ABM has proven to be a useful tool and methodological framework for the integration of qualitative and quantitative information, for the analysis of society-nature relationship of agricultural systems under an interdisciplinary and transdisciplinary approach at the micro and macro level.

It is expected that this technique will be used more frequently to support the design of agricultural public policy that transcend from local to higher level agricultural structures, however this will require a greater investment of time and money by policy makers.

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