Coupling Agent-Based Modelling with Geographic Information Systems for Environmental Studies—A Review

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Introduction

The exponential growth of the population is leading to a progressively transforming world (Liu, Chang, Chen, Zhou, & Feng, 2017). The increasingly inhabited areas are subject to high levels of various forms of stress, namely economic, social and environmental pressures (Bickel, 2017), surpassing the carrying capacity of those locations, i.e. "the largest number of any given species (e.g. *Homo sapiens*) that a habitat (e.g. Earth) can support indefinitely" (Shaker, 2015). The relationship between our behaviour and the carrying capacity of Earth can be viewed through the Ecological Footprint tool, which represents the "human demand on the planet's ability to provide renewable resources and ecological services" (WWF, 2016). At present, we need a yearly amount of 1.6 Earths to deliver the demand for goods and services, meaning that, in a business-as-usual scenario, human demand on Earth's regenerative capacity is expected to grow steadily and overshoot this capacity by approximately 75% by 2020 (WWF, 2016).

This increasing pressure adds to the threat of climate change (CC) (Bickel, 2017; Victor et al., 2014). CC has been one of the leading issues focused on the worldwide environmental agenda. The definition of the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report, is "*a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the*

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variability of its properties, and that persists for an extended period, typically decades or longer" (Cubasch et al., 2013). Although large-scale natural phenomena—such as extreme weather events—have always existed and are an intricate part of Earths' processes, research shows that they are exacerbated by CC (De Sario, Katsouyanni, & Michelozzi, 2013; Mann, Lloyd, & Oreskes, 2017).

Global mobilisation has begun throughout the last decades, with the latest relevant meeting having occurred in Paris in 2015. Leaders of the entire world gathered to focus on CC. The resulting Paris Agreement (UNFCCC, 2015) aims to "*strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty*". One of the ways to attain this is by "*holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change*". However, the 2018 *IPCC Special Report: Global Warming of 1.5 °C* (IPCC, 2018) assesses new scientific data of the climate system, as well as the associated impacts on natural and human systems, by focusing on a global warming change of 1.5–2 °C above temperatures in the pre-industrial period. In general, findings showed that many of the assessed impacts of climate change in the report have significantly lower associated risks at 1.5 °C compared to 2 °C, meaning that maximum temperature increase should not surpass the 1.5 °C mark.

The scientific community has recognised the urgency in this matter. Over 15 000 scientists have issued a notice to humanity (Ripple et al., 2017), where caution has been urged about the unsustainable ways humanity continues to undertake, and that adaptation measures to CC are dire. By implementing decisions and actions, these measures mobilise the capacity to reduce risk and vulnerability; seek opportunities; and build the capacity of nations, regions, cities, the private sector, communities, individuals, and natural systems to cope with climate impacts (Noble et al., 2014). Because of the delayed reaction to CC, we will deal with the effects of past emissions for at least 50 years. It is, therefore, dire to put these measures into action (Kennedy, Cuddihy, & Engel-Yan, 2007).

Sustainability

Sustainability is seen as a synonym for everything good and desirable in society (Holden, Linnerud, & Banister, 2014). It is a core term used nowadays to relate to the way planning and development should be perceived. However, what does it truly imply? The term sustainability development became broadly known after The Brundtland Report (Brundtland, 1987), where it was defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". However, due to the increasing complexity of modern society, this definition is no longer satisfying. Recently, defining the concept of sustainability has proved challenging, where scholars are currently attempting to determine a concept for sustainability and sustainable development for the present era. Walker

(2017) examines its meaning and shows how different perspectives can be taken when analysing sustainable development. Holden et al. (2014) attempt to create a definition for sustainable development which encompasses the four primary dimensions mentioned in the Brundtland Report (safeguarding long-term ecological sustainability, satisfying basic human needs, and promoting intra- and intergenerational equity). Ramcilovic-Suominen & Pülzl (2018) analyse several concepts of sustainability and sustainable development and how they are (re)adopted and reformulated in the current EU bioeconomy policy debate. However, despite all the different points of view or definitions, what is generally agreed upon is that sustainable development relies on social, economic, environmental and governance factors (European Commission, 2015; Ramcilovic-Suominen & Pülzl, 2018).

Sustainability is now imperative in our society, involving environmental, social and operational management strategies. Protection and maintenance of the landscape's integrity is a social responsibility and a commitment to pass on our heritage to future generations (Vaz, Cabral, Caetano, Nijkamp, & Painho, 2012). Thus, scientists and politicians will be challenged to reduce negative impacts of humans on the environment, by simultaneously keeping safe the economic and social benefits derived from them (Amato, Maimone, Martellozzo, Nolè, & Murgante, 2016; Esteves, Vaz, & Alves, 2017). As suggested by Vaz (2016), spatial analysis and particularly regional decision-making can have a leading role in assessing these paradigms from a local and regional planning perspective (Esteves et al., 2017).

GIScience in Practice

Monitoring urban development to assure future sustainability is fundamental, where decision support requires spatial information to be able to forecast development trends (Panagopoulos, Duque, & Dan, 2016; Vaz, 2016; Vaz, Kourtit, Nijkamp, & Painho, 2015). Agent-based models, cellular automata and micro-simulation models may be used to aid territorial policy and planning, presenting as an opportunity for dialogue between model builders and stakeholders (Batty, 2012; Esteves et al., 2017).

Land-use plans are fundamentally spatial, so the spatial visualisation component of GIScience is determinant to support territorial planning and decision-making (Alves et al., 2014; Brown, 2006; Campos et al., 2017; González, Donnelly, Jones, Chrysoulakis, & Lopes, 2013; Li & Kwan, 2017; and Vaz, 2016). Socio-economic and environmental issues and impacts are considered simultaneously, so by integrating evaluation methods and tools in geographic information systems (GIS), we can use computational methods to juxtapose traditional quantitative thinking to decision-making (Vaz, 2016). Creating tailor-made decision-making tools is vital to analyse baseline information and systematically predict potential impacts. Multiple-scale, multi-period, multiple-objective and multiple-user needs may be equally satisfied (Chrysoulakis et al., 2013). Consequently, it is a powerful driving engine in the technical and socio-organisational implementation of integrated platforms for informed analysis (Brown, 2006; González et al., 2013).

Significant advantages in using GIScience in environmental studies include (Batty, 2011; Caputo, Pasetti, & Bonomi, 2016; Chrysoulakis et al., 2013; Li & Kwan, 2017; Yan, Xia, & Xiang, 2014):

- A geovisualisation aspect of GIS, with the use of tangible visual representations and human visual abilities to generate insights about geographic problems. The visualisation may be in 2D or even 3D, greatly enhancing our ability to comprehend complex issues and patterns;
- Fast correlation between acknowledging local particularities such as morphology, prevalent economic activity, history and tradition, recent significant modifications and features;
- Select weak areas or performance areas to better research their features and orient local policies;
- Easily accomplishing sensitivity analysis and simulation of scenarios, varying the benchmarks and levels of importance of the parameters considered by the model;
- GIS determined features such as radiative exchanges, surface carbon concentration, surface characteristics, surface turbulent sensible and latent heat fluxes, urban heat island and heat waves, precipitation and air quality aid the assessment of urban metabolism components;
- A wide variety and combination of tools and models can be used to accurately assess environmental issues, taking elements from different software packages and building these directly into models as needed, creating an abundance of possibilities when it comes to performing good representations and simulations;
- Depending on the analysis type, large-scale operational models may be used (e.g. with agent-based modelling) or, when necessary, finer-scale models to simulate movement patterns and change, particularly the local movement of individuals and specific changes in territorial development (e.g. cellular automata models).

Agent-Based Modelling

Agent-based modelling (ABM) application in GIScience has been gaining popularity in system analyses, where it is seen as a new age of simulations (Dragicevic, 2008). Its capability to replicate the processes and dynamics that occur within a geographical system (Heppenstall, Crooks, See, & Batty, 2012) is a desirable trait in such studies, where the system's complex, nonlinear behaviour is addressed (Jokar Arsanjani, Helbich, & de Noronha Vaz, 2013). In ABM, the system being analysed is modelled as a collection of autonomous, heterogeneous and active decision-making entities called agents, where each of these have diverse knowledge and abilities and can interact with one another and their environment, by individually assessing its situation and deciding an outcome based on a set of rules inputted into the system. The behaviour of the whole system results from the aggregated individual behaviour of each one of these agents (Ausloos, Dawid, & Merlone, 2015; Crooks, 2015).

Local understanding is therefore increased through bottom-up analyses, independent of all scales and constrictions (Crooks, Malleson, Manley, & Heppenstall, 2019; Heppenstall et al., 2012; Jokar Arsanjani et al., 2013). Contrary to reducing the system to the idea that the territory operates from the top-down where results are filtered to its individual components, ABM adopts a reassembly approach, leading to an individualistic bottom-up approach for planning the geographical form and creating public policy (Crooks, 2010, 2015).

ABM has been the resource to undertake many recent studies in several realms, such as in GIScience, ecological and social systems, social and human sciences, urban systems, or land-use systems and science (Dragicevic, 2008). There has been a longlasting development of ABM: from the emergence of theoretical and technological advances that lead to the invention of the computer, Thomas Schelling's 1971 use of a cellular automata model to define segregation patterns, to the evolution of autonomous agents that move freely from the restrictions of their cells, into present studies in, e.g. environmental modelling or the impact of policy in geographical areas (Heath, 2010). Heppenstall et al. (2012) and Crooks et al. (2019) mention a wide array of applications for ABM. The ability to link agents to geographical locations is crucial, as most everything is connected to a place, allowing modellers to ponder on how these agents or their aggregations are fluid in space and time (Crooks, 2015).

Methodology

A region's environmental behaviour can be understood by resorting to tailor-made information systems so that effective strategic methodologies for territorial coordination can be defined (Catalán, Saurí, & Serra, 2008; Hinkel et al., 2014; UN, 2007). Using GIScience to produce different scenarios is key to integrate local, urban or regional processes with ABM approaches, presenting itself as an innovative combination of factors in determining the sustainable development of an area.

The following questions triggered this review: how have ABM and GIS been combined in recent studies to determine environmental issues? Do these methodologies aid in sustainable planning for the region? Framed to no particular study area, it aims at highlighting some of the most used methodologies concerning the use of GIS technologies coupled with ABM.

Interest is given to the support these studies might provide to both researchers and policymakers. For researchers, it may provide insights into the assessment of the environmental, economic and social affairs, as well as development elements to measure environmental sustainability in different contexts. On the other hand, decision-makers may use the clear information produced by these models to propose greener protection policies that are more effective, so that the economic performance may be balanced with a sustainable performance (Piña & Martínez, 2016).

To collect research papers on the coupled use of ABM and GIS, the methodology in Fig. 1 was followed.

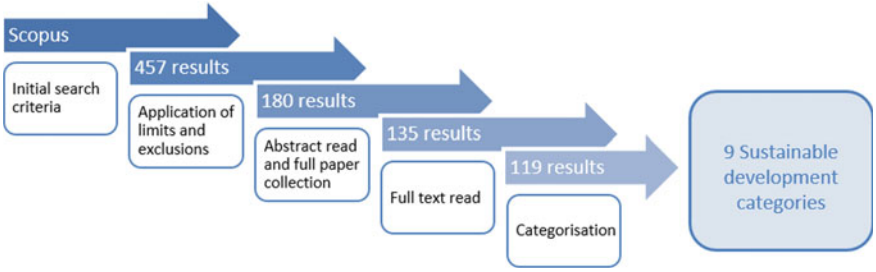

Fig. 1 Methodology for paper categorisation

Four initial web-based searches were made with the Scopus database, using the following criteria:

(1) (TITLE-ABS-KEY (agent-based AND modelling) AND TITLE-ABS-KEY (geographic AND information));
(2) (TITLE-ABS-KEY (abm) AND TITLE-ABS-KEY (gis));
(3) (TITLE-ABS-KEY (abm) AND TITLE-ABS-KEY (geographic AND information));
(4) (TITLE-ABS-KEY (agent-based AND modelling) AND TITLE-ABS-KEY (gis)).

These terms were searched within the article title, abstract and keywords of the papers. This search initially resulted in a total of 457 documents, where it intended to take account of the multidisciplinary and historical aspect of this domain area, to have a grasp on how they have been used throughout different subjects and time.

After collecting pertinent information, limits and exclusions were applied to the initial results, where the refinement of the search criteria was based on:

(1) (TITLE-ABS-KEY (agent-based AND modelling) AND TITLE-ABS-KEY (geographic AND information)) AND (EXCLUDE (SUBJAREA, "BUSI") OR EXCLUDE (SUBJAREA, "MEDI") OR EXCLUDE (SUBJAREA, "PHYS") OR EXCLUDE (SUBJAREA, "MATE") OR EXCLUDE (SUBJAREA, "BIOC") OR EXCLUDE (SUBJAREA, "ECON") OR EXCLUDE (SUBJAREA, "ARTS") OR EXCLUDE (SUBJAREA, "CENG") OR EXCLUDE (SUBJAREA, "DENT") OR EXCLUDE (SUBJAREA, "PHAR") OR EXCLUDE (SUBJAREA, "CHEM") OR EXCLUDE (SUBJAREA, "IMMU") OR EXCLUDE (SUBJAREA, "NURS") OR EXCLUDE (SUBJAREA, "PSYC") OR EXCLUDE (SUBJAREA, "VETE")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "ch") OR LIMIT-TO (DOCTYPE, "re") OR LIMIT-TO (DOCTYPE, "bk") OR LIMIT-TO (DOCTYPE, "ip")) AND (LIMIT-TO (LANGUAGE, "English"));
(2) (TITLE-ABS-KEY (abm) AND TITLE-ABS-KEY (gis)) AND (EXCLUDE (SUBJAREA, "PHYS") OR EXCLUDE (SUBJAREA, "BUSI") OR EXCLUDE (SUBJAREA, "MATE") OR EXCLUDE (SUBJAREA, "MEDI")

OR EXCLUDE (SUBJAREA, “CHEM”) OR EXCLUDE (SUBJAREA, “IMMU”) OR EXCLUDE (SUBJAREA, “BIOC”) OR EXCLUDE (SUBJAREA, “CENG”) OR EXCLUDE (SUBJAREA, “ECON”) OR EXCLUDE (SUBJAREA, “VETE”)) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “ch”) OR LIMIT-TO (DOCTYPE, “re”) OR LIMIT-TO (DOCTYPE, “er”) OR LIMIT-TO (DOCTYPE, “ip”)) AND (LIMIT-TO (LANGUAGE, “English”));

(3) (TITLE-ABS-KEY (abm) AND TITLE-ABS-KEY (geographic AND information)) AND (EXCLUDE (SUBJAREA, “EART”) OR EXCLUDE (SUBJAREA, “PHYS”) OR EXCLUDE (SUBJAREA, “MATE”) OR EXCLUDE (SUBJAREA, “MEDI”) OR EXCLUDE (SUBJAREA, “BUSI”) OR EXCLUDE (SUBJAREA, “BIOC”) OR EXCLUDE (SUBJAREA, “CHEM”) OR EXCLUDE (SUBJAREA, “IMMU”) OR EXCLUDE (SUBJAREA, “ARTS”) OR EXCLUDE (SUBJAREA, “CENG”) OR EXCLUDE (SUBJAREA, “ECON”) OR EXCLUDE (SUBJAREA, “HEAL”) OR EXCLUDE (SUBJAREA, “PHAR”) OR EXCLUDE (SUBJAREA, “VETE”)) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “ch”) OR LIMIT-TO (DOCTYPE, “ip”)) AND (LIMIT-TO (LANGUAGE, “English”));

(4) (TITLE-ABS-KEY (agent-based AND modelling) AND TITLE-ABS-KEY (gis)) AND (EXCLUDE (SUBJAREA, “BUSI”) OR EXCLUDE (SUBJAREA, “PHYS”) OR EXCLUDE (SUBJAREA, “MATE”) OR EXCLUDE (SUBJAREA, “MEDI”) OR EXCLUDE (SUBJAREA, “BIOC”) OR EXCLUDE (SUBJAREA, “ECON”) OR EXCLUDE (SUBJAREA, “ARTS”) OR EXCLUDE (SUBJAREA, “IMMU”) OR EXCLUDE (SUBJAREA, “CENG”) OR EXCLUDE (SUBJAREA, “CHEM”) OR EXCLUDE (SUBJAREA, “PHAR”)) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “ch”) OR LIMIT-TO (DOCTYPE, “re”) OR LIMIT-TO (DOCTYPE, “bk”) OR LIMIT-TO (DOCTYPE, “er”) OR LIMIT-TO (DOCTYPE, “ip”)) AND (LIMIT-TO (LANGUAGE, “English”)).

This way, exclusions were applied to the study fields of veterinary, psychology, nursing, immunology and microbiology, chemistry, dentistry, pharmacology, toxicology and pharmaceutics, health professions, economics, econometrics and finance, chemical engineering, arts and humanities, biochemistry, genetics and molecular biology, business, management and accounting, medicine, materials science, physics and astronomy. Conference papers and conference reviews were also discarded from the initial selection.

The search was this way limited to the fields of computer science, engineering, social sciences, mathematics, environmental sciences, agricultural and biological sciences, earth and planetary sciences, energy, decision sciences, multidisciplinary, and undefined. Articles, reviews, book chapters, articles in press, books, and errata that were written in the English language were otherwise considered.

A total of 180 papers were found from this secondary search. The abstracts were read, and only the ones related to the environment were selected. The criteria used was to choose the ones that mentioned subjects in natural resource management,

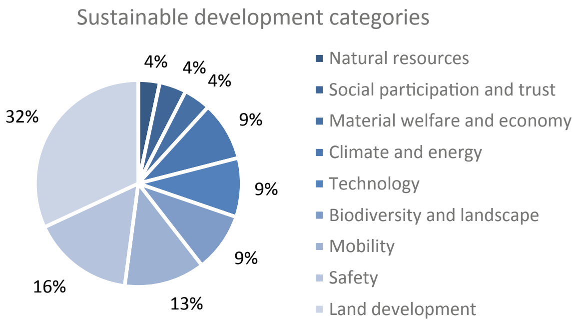

Fig. 2 Amount of studies per sustainable development category

conservation and biodiversity, environmental assessment, sustainable development, environmental health, wildlife management, sustainable building, water resources, land systems, policy and law, climate change, quality of life, energy and renewables. Besides framing the subject area to the environment, a further selection was made upon reading the abstracts, where studies from the same authors and study area were discarded, having retained only the most recent one. Other rejected results were the ones where we were unable to obtain the full text. This new selection yielded a total of 135 results.

Full-text reading was initiated at this phase, and another 16 papers were discarded due to further analysis revealing them not being pertinent to this review. A final tally of 119 results was obtained, for studies ranging from 1998 to 2019.

A final table was created, where the final results are analysed and distributed between nine sustainable development categories: natural resources, social participation and trust, material welfare and economy, climate and energy, technology, biodiversity and landscape, mobility, safety and land development (Fig. 2).

Results and Discussion

In this review, an effort has been made to scrutinise the results above to demonstrate the wide variety of fields that the coupling of ABM and GIS can encompass. An array of information has been collected, relating to all sorts of study fields, where predominant keywords are listed in Table 1. 65 of the articles were published in repeated publications (Table 2).

As previously mentioned, from the articles that were analysed, ABM coupled with GIS technologies were used to determine land-use development 38 times, 19 for safety, 15 for mobility, 11 for biodiversity and landscape, 11 for technology, 11 for climate and energy, 5 for material welfare and economy, 5 for social participation and trust and 4 for natural resources (Fig. 2).

ABM and GIS have been used for complex system analysis and simulation for quite some time. A result from 1996 was listed but was immediately disregarded, once the ABM keyword that was found related to something else than agent-based

Table 1 Ten most repeated keywords from selected papers

Keyword	Count
Agent-based models	88
GIS	50
LUCC	25
Cellular automata	9
Complex systems	6
Simulation	6
Decision support system	5
Geosimulation	5
Simulation model	4
Complexity	3

Table 2 Repeated publications in different journals

Journal	Articles
International Journal of Geographical Information Science	15
Computers, Environment and Urban Systems	7
Transactions in GIS	6
Journal of Geographical Systems	5
Ecological Modelling	4
Environment and Planning B: Planning and Design	4
Journal of Environmental Management	3
JASSS	3
Environmental Modelling and Software	2
Natural Hazards	2
Waste Management	2
Environmental Modelling and Software	2
Simulation Modelling Practice and Theory	2
Understanding Complex Systems	2
Geocarto International	2
ISPRS International Journal of Geo-Information	2
Understanding Complex Systems	2

modelling. So, from the initial search, one realises that steps have been taken to further these studies at least since 1997, where the 1997 International Conference on Spatial Information Theory (COSIT 1997) had started to analyse the issue at hand (Hirtle & Frank, 1997). It was only until 2004 and 2005 that scientific production increased drastically for this subject area, where up until then, there was a scarce work yield. Looking at the final correspondent selection, 2009 was the year that environmental studies linked to the coupled use of ABM with GIS had a more profuse

Table 3 Amount of coupled ABM and GIS results per year for the initial search and the final paper selection and percentage of the final selection in relation to the initial search

Year	Initial search	Final selection	%
1996	1	0	0
1997	1	0	0
1998	3	1	33
1999	0	0	0
2000	2	1	50
2001	2	1	50
2002	3	1	50
2003	6	3	50
2004	9	1	11
2005	14	2	14
2006	16	1	6
2007	17	4	24
2008	26	4	15
2009	40	11	28
2010	24	8	33
2011	25	6	24
2012	26	7	27
2013	50	12	24
2014	39	8	21
2015	41	11	27
2016	34	9	26
2017	34	7	21
2018	32	16	50
February 2019	12	5	42
Total	457	119	26%

production. By analysing Table 3, one can see that the percentage of environmental studies concerning the total amount of papers from the initial search is continuously varying, although, in the last two years, it corresponds to roughly half the production.

In respect to the coupling of these technologies, some general remarks can be made before diving into each of the sustainable development category analysis. Overall, these ABM and GIS were not used alone, where they were also combined with other types of tools, such as mathematical or computational ones, depending on the subject being analysed. Game theory was an interesting take used in three studies, where agents were programmed to find the best strategy to improve results.

Another general characteristic is the multitude of subjects that are analysed in the 119 final paper selection. Even within the same subject area (e.g., land use), studies vary widely and are frequently applied in different manners, even though the basic tools that are used are the same. Study areas are also wide-ranged, covering sites from all over the world, for both developed and undeveloped countries. By analysing the scale application of the models, it can also go from the local to the regional scale.

In terms of aid in policymaking, it is a significant aspect for most studies, once each of the created models intends to learn how to contribute to the solution of a specific issue. By allowing to better understand the problem at hand, in most cases, scenario simulation is possible, and through result analysis, key management options can be adopted, focusing resources to the best possible solution. This possibility to create different scenarios speaks to the flexibility of these tools, where some of the models saw suited application to various subjects or study areas, presenting as a significant advantage. In terms of limitations, many of the models mentioned the oversimplification of input data, where it is considered a necessary evil to better interpret results. However, these results may also leave out critical aspects of the analysis, revealing to be a delicate task finding a balance between too little and too much information.

Another limitation was the lack of a suitable benchmark for the studies, rendering them unable to be evaluated (Grimm et al., 2010). Being a relatively recent technology, and considering the wide range of application, there is still no standard format for documenting and communicating ABMs, and validation of the methodology and respective results remains diverse throughout the studies, where no standard validation or verification method exists for these models. Therefore, there is limited replicability, an undesired trait for a scientific tool. Grimm et al. (2010) have attempted to overcome these limitations by creating his overview, design concepts and details (ODD) protocol, by which ABMs can be documented through a basic format and a standard structure. This protocol will enable the reader to better understand the model descriptions, once they are written in a more complete and efficient fashion. Replication can be enhanced, and the ABM can, therefore, be considered as a more robust scientific tool (Grimm et al., 2010). Müller et al. (2013) have recently extended this protocol to the ODD+D, incorporating options to describe human decision-making.

In terms of software, several packages were mentioned, being the most frequent ones NetLogo, GAMA, ArcGIS and Repast. It is worth mentioning that different types of software were frequently used together in the same methodology, taking advantage of the most robust features of each one.

Many of the studies considered future work on their models, meaning that the limitations were recognised and continuous enhancement of the studied model was deemed necessary.

For the analysis in the following sub-sections, only literature from 2015 to February 2019 was considered, once the aim is to analyse the most recent work available in the field of ABM and GIS. All studies have a spatial component to them, where those that did not have one were immediately discarded. The analysis will be based on the number of papers that exist for each category, for the most significant amount of analysed papers (land development), to the smallest (natural resources). In respect to the analysis of the studies within each sub-section, no particular order was followed.

Land Development

Urban growth, urban redevelopment, urban transformation and urban planning were four of the keywords used in studies that, in one way or another, proceeded to analyse land use/cover change (LUCC) to find solutions for an environmentally related issue. Many of these studies were centred on LUCC, and how to sustainably do so in order to minimise negative impacts.

Tan, Liu, Zhou, Jiao, and Tang (2015) and Ahlqvist, Khodke, and Ramnath (2018) use game theory in their models, albeit not entirely in the same manner. The first authors use the mathematical method of game theory to quantitatively analyse the agents' behaviours, how their decisions are interrelated, and how they determine land-use change. On the other hand, Ahlqvist, Khodke, and Ramnath (2018) use a multiplayer online game to create a simulation environment that can engage actual real human stakeholders in a role-playing game, where they can generate empirical data to calibrate agent attributes and behaviours. Although the study is primarily an educational tool to convey the key aspects of the Green Revolution in developing countries, these authors find that replacing coded agents with real individuals can identify emergent behaviours typically expected from complex systems.

QuanLi, Kun, GuiLin, and YuLian (2015) use a different approach, combining an ant colony optimisation artificial intelligence algorithm with ABM to analyse non-point urban and agricultural water pollution from LUCC. This algorithm allows simplifying rule construction for agents, which leads to enhanced simulation accuracy. Though innovative, they, however, find that the ant colony optimisation algorithm is not well suited for all land-use types.

For the rest of the studies, they are, in general, a straightforward analysis of LUCC by using ABM and GIS. Barau and Qureshi (2015) analyse investment-driven land fragmentation (patterns and characteristics) and its ecological implications; Giełda-Pinas, Dzieszko, Zwoliński, and Ligmann-Zielińska (2015) assess ecological management practices and land-use change impacts when managing Lakeland landscapes; Li, Oyana, and Mukwaya (2016) study the LUCC at a national scale in Uganda; Cantergiani and Gomez Delgado (2016) study urban growth by including social and economic factors into the model; and Alghais and Pullar (2018) model future land-use patterns through population estimates and planning policies.

As for aid in policymaking, all studies revealed themselves as essential tools for decision-making. Stakeholders can use the simulation or scenario results to see how real-world human action influences the territory, providing information on how specific environmental, economic and/or social characteristics may be affected, which can allow them to develop sustainable planning and policy options.

Safety

Although not directly associated with the environment, safety issues were also considered in this analysis. CC contributes to extreme natural events to which populations need to cope with. Safety strategies can be developed by using ABM and GIS, being considered as important resources to, e.g. quickly allocate relief teams or simulate evacuation strategies. These studies also analysed other pertinent questions, such as risk analysis related to insurance payouts or even focussing on the disaster recovery processes.

Torrens (2015) and Hooshangi and Alesheikh (2018) address the earthquake response issue, although with a slightly different approach. Torrens (2015) intends to evaluate how human populations respond to the built environment in an earthquake event, by unifying process modelling, GIS and the virtual representation of the world. The second authors created a simulation model in post-earthquake urban search and rescue operations, designing it flexible enough to adapt to the environment and consider incompatible time-spatial and behavioural complexities. For both cases, no validation of the model is possible because there is no ground truth data of their study area, although Hooshangi and Alesheikh (2018) did do an uncertainty analysis. As for assisting in policymaking, Torrens (2015) gives a better representation of the world through the use of 3D mesh modelling and GIS, while Hooshangi and Alesheikh (2018) can provide such an analysis that timely and accurate decisions can be made in an earthquake crisis. Although not directed solely to earthquake occurrences, Na and Banerjee (2019) model evacuation of no-notice natural disasters with the use of agent-based discrete-event simulation, where they apply it to a large-scale earthquake evacuation. With this, they intend to contemplate scenarios with multiple types of evacuees and evacuation vehicles to improve evacuation strategy in a no-notice natural disaster. Like the previous authors, Lichter, Grinberger, and Felsenstein (2015) create a model with web-mapping services, ABM and GIS to generate and divulge outcomes in disaster management to a broader audience. The aim is to use a network community-based approach to use the internet as a facilitator so that stakeholders can improve access to information to enhance resilience to shocks. They considered two working scenarios: an earthquake event and a missile attack.

Widener, Horner, and Ma (2015) and Yang, Mao, and Metcalf (2019) analyse response and evacuation for hurricane events, respectively. While the first seek optimal locations for relief teams during simulation hurricane events, the latter simulates the hurricane evacuation process by using an empirically grounded model that can be adapted to other coastal areas. Therefore, the study made by Widener et al. (2015) can aid decision-makers to understand the potential of relief teams to encourage non-evacuees to move to a nearby shelter, while Yang et al. (2019) can help design more reliable future hurricane evacuation plans in the Florida Keys.

On the other hand, Eid and El-adaway (2017) study disaster recovery processes, representing recovery dynamics on the impacted community based on the decision-making processes, interactions and learning behaviours. Although their study area was subject to hurricane events, the authors intend to test their model on other problem domains. The main advantage to decision-making upon disaster recovery is that it may increase the communities' welfare by better guiding the redevelopment processes so that balanced short-term redevelopment goals and long-term social vulnerability reduction goals are met.

Floods are also a study subject in three of the selected papers. Liu and Lim (2016) examine flood evacuation planning, where their ABM and GIS models provide escape instructions for vulnerable households located within a 15 km service area and proposes locations for new shelters. Dressler, Müller, Frank, and Kuhlicke (2016) study the performance of disaster management and understand how it is affected by change, while Dubbelboer, Nikolic, Jenkins, and Hall (2017) analyse changes in flood risk and the role of insurance in this dynamic. In general, all three studies mention the oversimplification of the input data, and how more complex data may forego result comprehensibility and transparency. As for aid in policymaking, Liu and Lim (2016) state that it may help stakeholders understand the big picture of large-scale evacuation and provide a feasible and organised way to manage the evacuation situation. Dressler et al. (2016) create a virtual lab that rapidly implements new ideas and tests hypotheses to obtain a better mechanistic understanding of the system behaviour, while Dubbelboer et al.'s model (2017) helps assess public–private partnerships and understand how socio-economic development can affect levels of surface water flood risk.

Although it may provoke some flood-like situations, a different study for tsunami events was made by Makinoshima, Imamura, and Abe (2018). The authors study tsunami evacuation by using real-time evacuation data into the simulation so that they can forecast congested areas during the disasters and rapidly estimate an evacuee population distribution at each evacuation site. Although no car agents are considered in the simulation, it is of great importance in decision-making once it allows the evaluation of evacuee congestion both in buildings and bottlenecks in the city.

Wirth and Szabó (2018) and Macatulad and Blanco (2018) simulate building evacuation. These local scaled studies use ABM and GIS (although Macatulad and Blanco (2018) use 3D-GIS features for model input) to determine evacuation times for their study area as well as panic rate in agents, where, in each study, panic was measured differently. Aid for decision-making may come in the form of a better understanding of how to address public safety issues, in terms of architectural and design aspects, and proper determination of the evacuation protocol and regulations of space. An adequate measure of the effects panic can have in the egress of building occupants may also be determined.

Bandyopadhyay and Singh (2018) study urban fire emergency response plans, which can support in establishing different theories and observe and ascertain exceptional patterns, that is, to detect where attribute variations help determine the micro-deficiency in urban infrastructure related to urban emergency planning.

Mobility

In terms of mobility, it is integrated into this review due to climate change issues. Considering that the more mobility issues are sustainable, a favourable effect should be verified in what refers to air pollution and emissions.

Three studies were found that analyse waste management and the optimal path to collect and manage these residues. Nguyen-Trong, Nguyen-Thi-Ngoc, Nguyen-Ngoc, and Dinh-Thi-Hai (2017) examine municipal solid waste management, where the use of GIS analysis, equation-based model and ABM will allow simulations to optimise the strategy for collection and transportation of municipal solid waste to improve the current collection system. Elia, Gnoni, and Tornese (2018) use a hybrid simulation model of system dynamics, ABM, GIS and discrete events simulation to analyse dynamic collection schemes for Waste from Electric and Electronic Equipment (WEEE). The considered advantage is that, unlike fixed services, a dynamic collection can allow for control of management costs and reduction of the intensive use of vehicles due to the flexibility of the service. This way, environmental performance can be enhanced when designing adequate WEEE collection schemes. The third study was made by Kim, Kim, and Kiniry (2018), who intend to pinpoint optimal locations for biomass storage facilities. With this simulation, some of the main biorefinery concerns may be resolved, such as a steady supply of material, uniform feedstock properties, stable feedstock costs and low transportation costs. This study will allow an experimental performance analysis of approaches to the sharing of shortest path information in a large-scale transportation scenario.

Analogous studies as the previous were made, but instead of dealing with waste management, Démare, Bertelle, Dutot, and Lévêque (2017) and Kin, Ambra, Verlinde, and Macharis (2018) analyse goods distribution and their respective logistics. The first authors use ABM, GIS and graph theory to create a behavioural model of a logistic system to describe flows throughout the Seine axis (France), enabling stakeholders to understand at a multi-scale level how the logistic system works and how the actors dynamically structure and organise the flows within a territory with decentralised decisions. Kin et al. (2018) tackle last-mile deliveries, creating a synchronisation model for the Belgian inland transport system that simulates modal choice alternatives. The resulting model may test new ideas in a risk-free environment so that they may assess what-if scenarios prior to implementation. Tucnik, Nachazel, Cech, and Bures (2018) use ABM, GIS and pathfinding algorithms in a large-scale setting to analyse the experimental performance of approaches to the sharing of shortest path information.

Other studies use traffic simulation to evaluate transport networks (Bonhomme, Mathieu, & Picault, 2016), quality of life (Makarov & Okrepilov, 2016), transport network expansion (Jacobs-Crisioni & Koopmans, 2016) and dynamic transport systems (Lu & Hsu, 2017). In general, these studies aid decision-makers in enhancing and enabling better decisions when intervening in transport systems.

Biodiversity and Landscape

Biodiversity and landscape issues included in this review encompass studies related to the dispersion of species throughout the environment, either through a negative (invasive species) or positive (species protection) view.

Anderson and Dragićević (2018) study the dispersion of an invasive insect infestation with a dynamic spatial network so that stakeholders can better understand, measure and analyse the influence that geographic space and network structure have on network dynamics so that in an ecological management perspective, the characterisation of dispersal patterns may be particularly useful. On the other hand, Gray et al. (2017) study the effects on biodiversity in bushmeat hunting by using a 4P (purpose, processes, partnerships and products) framework for participatory modelling so that the issue of bushmeat hunting sustainability may be turned into a matter of common concern at a sub-regional scale and to stimulate villagers to engage in community-based hunting management. Three studies analyse species distribution, where Heinänen et al. (2018) use hydrodynamic modelling to model and simulate realistic distributions, movements and migration of the Atlantic mackerel so that movements present in nature can be reproduced to better understand species characteristics. This model may also be applied to other species and pressures. Similarly, Carpenter-Kling et al. (2019) simulate the at-sea movement and distribution of a land-breeding marine predator to understand their foraging ecology and life-history traits, allowing for high-resolution information about location and foraging behaviour of wild animals. Scott, Middleton, and Bodine (2019) simulate population dynamics of the Santa Cruz Island fox and to determine the average number of years that the fox population can exist before going extinct in the absence of conservation efforts.

Technology

This section exists to consider studies that have no actual study area or application subject, only defining technical issues for ABM, which was something that we thought could not be ignored at this time.

For that, de Sousa and da Silva (2016) intend to create a spatial simulation in the context of GIS for non-programmers by creating a domain specific language for spatial simulation scenarios (DSL3S). This language facilitates communication between programmers and analysts and other stakeholders lacking programming skills, and GIS analysts may be able to focus their work on the actual modelling and ignore issues that are specific to programming, data input or platform dependencies. Vahidnia, Alesheikh, and Alavipanah (2015) create a model to simulate a system for moving reasoner agents by combining a multi-agent system with GIS, logical deduction and qualitative reasoning. The designed framework can potentially be applied for task-oriented problems such as vehicle motion planning, disaster management and military scenarios. Lastly, Gallagher, Richardson, Ventura, and Eddy

(2018) use R to generate synthetic population ecosystems of the world (SPEW) that may be applied to any type of agent and environment or location due to the flexible data input, enhanced user control in both data input and sampling methodology and automatically generated summary reports for each region.

Climate and Energy

CC is an important issue in discussion worldwide. As mentioned, temperature rise must be drastically controlled to warrant conditions for future generations of all species worldwide. This category considers studies that relate directly to the production or management of energy and the creation of infrastructures to encourage non-motorised transportation.

Robinson and Rai (2015) and Lee and Hong (2019) analyse the adoption of renewable energy (solar photovoltaic) for a given area, where the first use empirical information, ABM and GIS to do so, while the latter use ABM, GIS and logistic regression. These studies may help to successfully predict solar technology adoption so that policy and incentive structures may be adequately designed, and the electricity generation strategy planned and managed accordingly.

Imran, Schröder, and Munir (2017) determine suitable locations for the installation of a biogas power plant so that its operation can run smoothly and economically. Aziz et al. (2017) study the development and expansion of walk–bike infrastructure in cities so that the impact of infrastructure expansion in terms of the number of people using the expanded walk–bike facilities can be assessed beforehand.

Material Welfare and Economy

In what respects to the material and welfare section, it comprehends studies that determine economic characteristics of the territory, whether by studying individual economic behaviours or by identifying how the level of management of interconnected infrastructures may bring economic gains.

Filatova (2015) created a Risks and Hedonics assessment in Empirical Agent-based land market model (RHEA LMM) to explore the land market's performance under various microeconomic behaviours of individual agents. This model will aid decision-making in understanding the aggregate patterns and economic indices that outcome from the many individual interactions of the economic agents. By doing so, decision-makers are then able to explore the extent of changes in the economic system, so that they may be able to, e.g., respond adequately and timely to adverse consequences of climate change, as well as determine the impact of adaptation policies.

Bhamidipati, van der Lei, and Herder (2016) combine multi-sector infrastructures (pavements, sewer pipes, electricity sub-stations, bridges, etc.) to understand the implications of their interconnectedness to define the optimal level of asset management. This will allow stakeholders to design and realign infrastructure systems to cope with the consequences of, e.g. CC. By being aware of the vulnerabilities of their infrastructures and the ones that are interconnected, stakeholders can collaborate with other asset managers to repair their assets.

Social Participation and Trust

This section focuses on studies that are directly related to the individual, which studies their level of involvement and where they may make a significant difference through their actions.

The location of creative industries, that is, industries that are mainly concerned with the generation or exploitation of knowledge and information, may shape a given territory in a significant way. This is the focus of Liu, Silva, and Wang (2016), where they explore the dynamics of the interactions between creative industries' development and urban land use. With their work, the authors can determine the potential that creative industries have for urban regeneration, innovation and sustainable development. By understanding location preferences for these industries, their influence on the urban landform may be understood to help formulate customised plans and policies.

In terms of green infrastructure, Zidar et al. (2017) compare different green infrastructure implementation strategies by individuals to aid in designing financial instruments for private property owners, as well as determining physical and financial barriers to program delivery.

Natural Resources

The natural resources section is considered for the inclusion of studies that revolve around issues such as ecosystem recovery, water management, sustainable tourism practices and natural resource allocation. Although four papers were selected for this review, none are later than 2015 (the most recent one is from 2012), so an in-depth analysis will not be made at this time for this section.

Conclusions

The increasing rate of population growth has had a gradual negative impact on many systems on earth. Issues in this respect are greatly discussed, where the realisation has dawned that, whether in developed or under-developed countries, issues such as poverty, inequality, climate, environmental degradation, prosperity, peace and justice should be treated as a whole, so that a better, sustainable future can be an achievable solution for all mankind.

Studying sustainability is not an easy task. It usually comprehends extremely complex issues, with many variables and relationships between them that are hard to uncover. The use of suitable tools to aid in these complex issues is key to a proper analysis of the problem at hand. The famous quote "modelling for insights, not numbers" comes to mind (Huntington, Weyant, & Sweeney, 1982), where the potential of allying ABM to GIS is vast, and the complex interactions may be modelled to show spatial inequalities that are determined by economic, geographical, institutional and social factors (Esteves et al., 2017). Support in planning decisions is also an important aspect, where visualisation enhancement comes from taking alphanumeric data, flows, and processes and transforming them into a visual aid, geographically pinpointing the cause/effect of a given occurrence (Campagna, 2006).

As previously analysed, the selected papers have shown that there is a wide range of applicability for the use of ABM and GIS. Whether with just the use of these two technologies or by complementing them with other techniques, algorithms or theories, many issues related to environmental sustainability may be addressed. Even within different sustainability categories, studies with similar subject matter and aims may end up presenting diverse results. By realising the problem, researchers may create tools and models to address those issues so that they may solve them or aid stakeholders in perceiving the best solution possible, given the reality that is presented.

For the studied papers, in many of them a general remark was that the more complex the model is, the less transparent it becomes, reflecting in the ability to understand the achieved results. The challenges for creating an ABM are varied: ontological and epistemological issues, conceptual design, model implementation, etc. (Dragicevic, 2008). Therefore, a delicate balance between input information and model development should be taken to heart in order to minimise these limitations. Additional setbacks are related to validation issues and a lack of a suitable study benchmark to compare studies.

Despite these restrictions, we have had the opportunity to learn a great deal with the studies included in this review. They present themselves as valuable steps into the vast potential of the coupled use of ABM and GIS. We are still in the early stages, but the future seems promising.

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