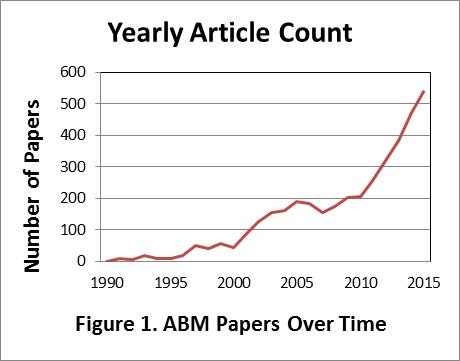
**The Usefulness, Uselessness, and Impending Tasks of Agent-Based Models in Social, Human-Environment, and Life Sciences**

(ABM overview/synthesis)

Authors: To be decided based on contribution

1. **OVERVIEW**

The use of agent-based models (ABMs; for definition see Section 4) has increased rapidly among various scientific communities over the last two decades. According to the Web of Knowledge (detail in Section 2), the number of articles reporting the development or use of ABMs has been steadily increasing in an exponential rate since the mid-1990s (Fig. 1), ranging across such research fields as ecology, human-environment science, epidemiology, land system science, and sociology. This increasing interest and use is largely rooted in ABM’s unique power of representing agent-environment interactions, local level information and heterogeneity, nonlinearity, feedback, and individual-level activity and decision-making (e.g., Gimblett 2002; Parker et al. 2003; An et al. 2005; An et al. 2014; NRC 2014). ABM’s are also useful for integrating data and models across multiple disciplines and for addressing problems across spatial, temporal, and organizational scales (An et al. 2005, An et al. 2014).

The increasing recognition and application of ABMs in a wide range of disciplines, as indeed predicated on the power of ABM, should not warrant overlooking or downplaying a series of challenges regarding ABM model validation, scalability, transparency, reusability, modeling of human decision making, hunger for data, and difficulty in handling big data (see Section 2 Background). These challenges, if not addressed with high priority in ABM research, may lead to inadequate or inappropriate ABM uses and results, and become constraints on advancing the science in question. Major advances in ABM’s notwithstanding, a range of challenges still beset ABM developers and users. These challenges include difficulty in model verification and validation, sharp learning curves for non-modeling experts (novices in particular), lack of common standards or protocols (with a few exceptions, e.g., Grimm et al. 2006, 2010), and paucity of transparency and reusability (e.g., Parker et al. 2003, An et al. 2005, An 2012, O'Sullivan et al. 2015). Equally (if not more) important, ABMs are largely developed either on a PC (for exceptions see Tang et al. 2011, Tang and Bennett 2011) or on an ad hoc basis with substantial variation in platforms, programing languages, model details and sophistication, and the modeler’s preferences. These variations reduce the capacity to facilitate high performance computing and handle big data, especially spatially and potentially temporally explicit data. These difficulties, in turn, may partially account for some hesitance, misuse, misunderstanding, or doubt about ABM (Couclelis 2002).

In the context of these challenges, the **goal** of this synthetic article is to advance the science and application of agent-based models (ABMs) in the social, human-environment, and life scienceswith the **objectives** of: 1) updating the state-of-the-science (particularly weaknesses and strengths) of agent-based modeling, 2) providing ways of improving ABMs (e.g., insights into available resources) in a set of carefully identified subareas, and 3) pointing out ABM-related impending tasks and future directions, especially areas of collaboration within and beyond the ABM community.

1. **BACKGROUND**

ABMs are increasingly used to address many empirical (e.g., studies focusing on social systems, life systems, and coupled human and natural systems; Bian 1997; Deadman et al. 2004; Evans & Kelly 2004; Crawford et al. 2005; An et al. 2006; Wilson 2006; Liu et al. 2007; Brown et al. 2008; Yu et al. 2009) and theoretical (e.g., Arthur 1999; Axelrod & Cohen 1999; Manson 2001) problems, which are axiomatically complex. Below we provide a literature review about ABM.

Agent-based modeling (ABM), or individual based modeling (IBM, named so largely by ecologists), or multi-agent systems (MAS; Parker et al 2003), is rooted on the fundamental philosophy of methodological individualism, which focuses on the uniqueness of individuals and interactions among them or between these individuals and the associated environment(s). Technologically, agent-based modeling has emerged and prospered with the advent of a new computer science paradigm since the 1980s, called object-oriented programming, along with increasingly available computing power and data. Researchers use ABMs for many reasons, which are related to the features of ABMs noted below.

First, ABMs have intellectual origin from, and substantially contribute to complexity science. Complexity science aims to understand complex systems, which often include heterogeneous subsystems, autonomous entities, nonlinear relationships, and multiple interactions among them (Arthur 1999; Axelrod & Cohen 1999; Crawford et al. 2005; Levin et al. 2013). ABM’s object-oriented programming capacity, e.g., representing the related entities and subsystems as agents at various, often hierarchical levels and employing flexible rules to mimic many complex relationships and interactions, just satisfies the needs of understanding complex systems. Such systems feature path-dependence, self-organization, difficulty of prediction, and emergence not analytically tractable from system components and their attributes alone (Manson 2001; Bankes 2002; NRC 2014). Hence it is suggested that the ABM approach be employed to understand, harness, and improve (rather than fully control) the system’s structure and function, taking innovative action to steer the system in beneficial directions (Axelrod & Cohen 1999).

Second, ABM’s have witnessed increasing adoption in social systems (e.g., Axelrod & Cohen 1999; Irwin & Geoghegan 2001; Crawford et al. 2005; Manson 2001; more recent ones), coupled human and natural systems (CHANS; Liu et al. 2007), and life systems (e.g., Eliassen et al. 2009, 2016; Giske et al. 2014; Grimm et al. 2006). Synonyms of CHANS include social-ecological (environmental) systems (SES) or human-environment systems (see Ostrom 2009 and Turner et al. 2003). These systems manifest the following features according to six empirical CHANS related (Liu et al. 2007) studies, which are also witnessed in many other sites (e.g., Irwin & Geoghegan 2001; Grimm et al. 2005; Messina & Walsh 2005; Malanson, Zeng, and Walsh 2006; Zvoleff and An 2014b): heterogeneity, reciprocal effects and feedback loops, nonlinearity and thresholds, surprising outcomes (observable as a result of human-nature couplings), legacy effects and time lags, and resilience (Liu et al. 2007; Levin 2012).

ABMs can address these CHANS or SES challenges because of their intrinsic, OOP-derived capacity to incorporate individual-level (e.g., heterogeneous subsystems, autonomous entities) information, to allow for multiple nonlinear relationships and interactions such as feedbacks, learning, and adaptation, to account for spatially and temporally variable information, and to integrate cross-scale and cross-discipline data and methods (An et al. 2005; NRC 2014). Another key value of ABM is the ability to represent human behavior more realistically by accounting for bounded rationality, heterogeneity, agent interactions, evolutionary learning and out-of-equilibrium dynamics and then combine this representation with environmental factors (Parker et al. 2003; Filatova et al. 2012; NRC 2014).

Third, building on the above strengths, agent-based modeling may provide a holistic, heuristic, and adaptive platform, enabling modelers better understand and improve the structure or functions of many empirical (e.g., human environment, land change) systems. Because this methodology explores dynamic paths, ABMs are especially useful when the processes under investigation involve abrupt changes, crises, and critical transitions related to social interactions and adaptive behavior. Therefore, according to National Academy of, ABMs are useful at the intervention design stage because they provide a means for projecting possible effects of policies or decisions ex ante (NRC 2014).

Challenges also abound in ABM literature and applications. It is reported that ABMs are very data hungry, lack of model transparency and model/module reusability, and are difficult to scale ABM models or findings from one level to another (Parker et al. 2003, An et al. 2005, An 2012, An et al. 2014; O’Sullivan et al. 2016). Another challenge is to adequately verify, validate, and analyze the model outcomes, including their sensitivity, which arises partially from the large amount of micro-scale information often embedded with varying levels of uncertainty and errors, (often) high numbers of parameters that are sometimes required in order to simulate agent behavior, and inadequate understanding of the system under investigation. Thus model performance is potentially sensitive to level of detail as well as stochastic elements, alternative decision models, and representation of spatial structure (Filatova et al. 2012).

When ABMs are largely not reusable, non-transparent, and difficult to be validated, it is very difficult, if not impossible, to compare ABMs from different sites or applications and thus generalize commonalities out of locale-specific details, thus limiting the usefulness of ABM in hypothesis testing and theory formulation (Rindfuss et al. 2008; An et al. 2014). Correspondingly, it is sometimes difficult to convince people what insights may come uniquely from ABMs instead of traditional equation-based models such as various types of regression models.

1. **METHODS & RESULTS**

**3.1. An Online Survey about ABM**

In order to characterize the temporal trend and disciplinary composition of ABM papers, we performed an online search based on Web of Knowledge. We used a combination of “agent based modeling" OR "agent based models" OR "individual based modeling" OR "individual based models" OR "multi-agent models" OR" multi-agent modeling" OR "multi-agent systems". Note that a dash between two words does not produce any differences in search outcomes—e.g., “agent based” is considered as identical as “agent-based”. Some terms, though relevant, are excluded in the search because they are either deemed too peripheral or derivative (e.g., individual modeling, object-based models). As a huge number of papers are returned if “topic” is used, we limited our keyword-based search to “title” only. To assure that the words are shown in the title exactly as we have listed (e.g., agent based models rather than agent …based …models), we used quotation marks for each keyword phrase, thereby excluding those bearing little relevance and limiting the number of returns.

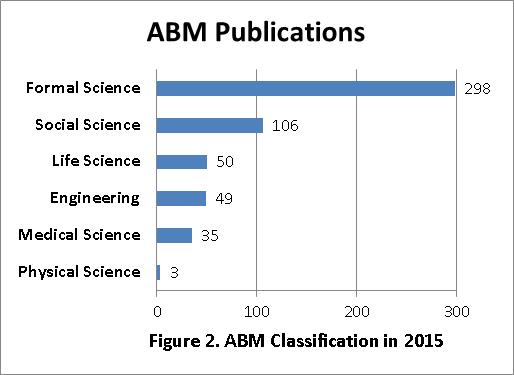
We then reviewed and classified the articles assembled in the above search by putting a year stamp on each of them, and classifying them into their corresponding disciplines based on their abstracts and keywords. We then aggregated these papers from their disciplines into a broader category of social sciences, life sciences, formal sciences, physical sciences, medical sciences, and engineering. The term “formal sciences” represents disciplines concerned with formal systems, such as logic, mathematics, statistics, theoretical computer science, information theory, game theory, systems theory, decision theory, and portions of linguistics (<http://en.wikipedia.org/wiki/Formal_science>; last accessed 10 March 2016).

**3.2 Email Survey**

To accomplish the goal and objectives outlined in Section 1, we performed a pilot survey of 27 (later expanded to 40) prominent scientists pertinent to ABMs and the related subfields from August of 2015 to March 2016 (Appendix 1 for more detail). The goal of the survey was to assure whether there is an urgent need, and if so whether it is the right time, to synthesize ABM work and come up with taskforce to address ABM challenges. Our selection of these people was based on the following criteria: 1) knowledge and experience in developing / using ABM, 2) reputation in publishing ABM related papers, or 3) experience and reputation in related domains or subfields that contribute to ABM, e.g., human environment science, land system (land change) science, biology, sociology, anthropology, and political science. When any one or more of these three criteria were met, we further considered the following two guidelines: 4) diversity in research fields—we tried to seek input from various research domains, such as those from as shown in Criterion 3; and 5) diversity in career stages—we tried to survey junior, mid-career, and established researchers.

From November 2016 to January 2017, we administered a second round survey of 40 prominent scientists (the same as the one above; detail in Appendix 2) pertinent to ABMs. This round of survey aimed to know the perceived areas of research in which ABM is very powerful, the challenges/issues that ABMs could potentially help with but not well addressed, the bottleneck challenge(s) that keep ABM from being more useful/acceptable, and how to solve or address such challenges if no constraints on budget, people power, and the like. As to critical issues to be addressed, we base our selection on 1) their significance to various dimensions of social, human-environment, and life science research; 2) the commonality of these issues that cross cut all possible research efforts employing ABMs; and 3) the likelihood of resolution. As an example, be it the land system science research to understand the causes of tropical deforestation or the practitioner community’s need to certify Payments for Ecosystem Services, there is a need for multiple-scale, spatially explicit models that not only account for immediate forest outcomes (e.g., what parts and how much of the forest will be cut and burned), but also for the length of use, fallow and return of secondary forest as affected by changing institutions or rules of resource governance. What are ABM’s strengths and weaknesses to address these needs? Can the weaknesses be improved such that robust model outcomes follow?

From February 2017 to April 2017, we administered a third round of survey of the same 40 scientists. This survey focused on familiarity of the six topic areas among the 40 researchers, specific issues within these six areas that deserve attention, and the domain areas of these 40 researchers.

**4. Results**

**4.1 Dynamics and range of ABM uses**

The outcome of the online search (Section 3.1) is shown in Figure 1 (placed at the beginning of this article) and Figure 2. It seems the number of ABM papers has been increasing rapidly, especially since 1991 when an exponential trend is observed. Out of the 541 papers published in 2015 (update with the 2016-17 data), formal sciences, social sciences, and life sciences take the vast majority of them (Figure 2). Note papers in land change or human environment systems were classified into the Social Science category. These findings have corroborated our claim about increasing application of ABM in a large number of disciplines, as well as our focus on ABMs in the in social, human-environment, and life science domains.

**4.2 Urgency and timing of synthesizing and improving ABM**

The first round of survey indicated that although ABM has many commonly agreed advantages (citation), it suffers a variety of problems including lack of model transparency and reusability, difficulty in model verification and validation, and difficulties in making use of big data and high performance commutating power. The vast majority of the surveyed researchers warranted the urgency and right timing of joint efforts that aim at addressing these problems or challenges (detail in Appendix 1). This survey directly contributed to identification of the topic areas we identified in the 2nd survey (Section 3.2).

**4.3 Six important topic areas**

According to feedback we received from the first-round (Section 3.1) and second-round (Section 3.2) surveys, we propose six difficulties or challenges that should be addressed with higher priority among others. They are each demonstrated below [for everyone—other ones? or edit the following].

1) *Modeling human decision making in ABM, especially decisions regarding their interaction with the environment*. There is increasing evidence that this topic is of prime interest. For instance, the PI’s review paper about modeling human decisions using ABMs (An et al. 2012) has become his mostly cited paper in the past three years (over 176 citations as of March 9, 2016) according to Google Scholar. This choice also comes from a suggestion from one of our invitees.

2) *ABM transparency and reusability*. This has been mentioned as one of the bottleneck problems for ABM community (e.g., Parker et al. 2003; An et al. 2014; NRC 2014) even though some important work has been conducted (e.g., the Open ABM node at [www.openabm.org](http://www.openabm.org)). Without adequate transparency and reusability, it is not only very difficult to verify and validate ABMs, but also wastes a large amount of resources such as modules and programming libraries that have been developed and tested by ABM experts and could have been reused.

3) *ABM verification and validation*. This has been a problem besetting ABM modelers and users for many years (e.g., Manson 2002; Parker et al. 2003; An et al 2005, 2014; NRC 2014), and many doubts arise from this difficulty (e.g., Couclelis 2002). Without robust model validation, the reliability of ABM cannot be established, limiting its usefulness and application in various contexts (An et al. 2014; Brown et al. 2008).

4) *Big data high performance ABM*. This emphatic topic comes from the increasing availability of big data such as high resolution remote sensing imagery and large detailed, human socioeconomic datasets (S. Wang et al. 2013). Currently ABMs are largely based on relative small or local scales, limiting the usefulness of ABM in large (spatial extent) and high resolution contexts—for a small set of exceptions that use parallel computing, see Tang et al. (2011), Tang and Bennett (2011).

5) *Integrated human-environment ABMs*: ABMs are useful in many contexts, but are not a panacea. Researchers should identify the types of research questions that ABMs of human-environment systems can answer or have answered, while other modeling approaches (econometric, spatial regression...) cannot or have not. Also issues revolve around harmonizing social and environmental data that are subject to various spatial and temporal extents/resolutions so that there is parity in model calibration/validation in both social and environmental dimensions. Models of environmental systems often are developed for relatively large spatial extents (GCM-climate, global change). Can and should the ABM community work to bridge to these types of model (see Rounsevell et al. 2011)? Other questions as below also are instrumental to developing and using integrated human-environment ABMs: How do we customize the complexity of the representation of ecological and human processes to the intended purpose of the model (exploratory or theoretical / participatory / descriptive or predictive)? How do the relative temporal scales of the ecological and human processes in the target system influence the representation of ecological processes (static/simple state transitions/dynamic) or the nature (tightness) of the coupling between ecological and human components of the model?

6) *Methodological issues of spatially explicit ABMs*: There is a whole basket of modeling issues that apply to spatially-explicit models but are not limited to them, e.g., effects of random number generators, the way to handle boundary conditions, effects of spatial structure and model type on ABM evaluation (e.g., via sensitivity analysis), the effects of spatial resolution and extent and data models on model calibration and validation, the possibility and benefits of employing alternative spatial representation (in comparison to the traditional Cartesian space)—e.g., adoption of relative space in ABM (An et al. 2015). Good decisions on these issues may be conducive to developing more robust ABMs.

1. **DISCUSSION AND CONCLUSIONS**

This article aims to air the emerging ABM issues, identify and outline critical *state-of-the-science* (topical subareas in particular) in ABM science, and provide a venue to seek resolutions. First, we bring several *compelling ABM problems and challenges* to the upfront *at the right timing* with approval from key community leaders and practitioners. At a time in which the use of ABMs is exploding, but maintains a series of unresolved challenges, this paper, with input from around 100 exceptional scientists with very diverse backgrounds (including modelers, users, domain experts), will likely best depict the state-of-the-science about ABMs, providing *incentives*, *inspirations*, and *directions* for many related fields. For instance, software engineers may develop more robust, user-friendly tools such as GUI based, programming free ABM platforms. Domain experts and potential users of ABM may know better where and how they can better employ, and contribute to the science of ABM in their own projects—e.g., human environment scientists may find specific applications in modeling human decisions that directly affect the environment.

This paper has engaged subfield experts to identify a set of *impending challenges in several topical subareas* so as to unify the relatively fragmented ABM endeavors through coordination, collaboration, and communication. This will help prioritize specific resources and activities in relation to ABM advances*,* leading to coordinated, joint efforts and initiatives to advance the science and technology behind ABM. There exist many CHANS or SES applications worldwide, but many fall short of strong convincing power in the usefulness (e.g., offering unique insights) of ABM. Though we do not intend to find a one-fits-all solution (which is impossible) in one paper or symposium, it is time to engage people power and resources, with higher priority, to address those challenges with a good chance of resolution and escalating influences on the rest challenges, and this paper is a precursor in this regard.

Additionally, with a clearer picture of ABM strengths, weaknesses, available resources, and impending tasks and future directions, more potential *users* or *developers*, and even commercial companies, will be attracted to engage more with the ABM community, allocating necessary resources to the science, technology, and application of ABM, enhancing ABM software and capabilities.

As a “byproduct” of the first two broader impacts, many disciplines or subfields that use and help advance ABM may benefit from such advances in ABM. For instance, human environment scientists may develop comparable ABMs (now comparability is very limited due to limitation in ABM reusability and transparency as aforementioned), distill commonalities from locale-specifics, test and generalize site-independent hypotheses, and thus ultimately formalize SES-applicable theories.

In conclusion, we call to assemble greater efforts and resources, including engaging the broader ABM community (developers/software engineers, users, domain knowledge experts), to not only ABM development and application, but also to education. Specifically, it would be highly beneficial for ABM researchers and practitioners to be aware of and comply with the following guidelines:

1) We need coordinated efforts, leveraging existing resources (e.g., <http://chans-net.org/>, <https://www.openabm.org/>, <https://www.comses.net/>) and reducing redundant investment of time, efforts, and fund.

2) Efforts should be devoted to lower the threshold of boarding ABM. ABM still has a sharp learning curve, which requires substantial skills and knowledge in computer programming and mathematics. If ABM “Lego” or “Mr. Potatohead” pieces can be crafted and made readily available (as open source or commercial products), more people, including children and people of less programming or mathematics background, can “develop” and use ABM.

3) We need to set up standards that are commonly accepted by ABM developers and users. As the ODD is increasingly adopted, other protocols, languages, and/or morals may need to be established about sharing modules and code, documenting models, and dealing with related authorship and data confidentiality issues (e.g., sensitive data protected by IRB). In this regard, the platform Jupyter (<https://jupyter.org/>) may be a good start.

4) We need to facilitate relatively easier, frequent communication between domain knowledge (e.g., for human decision making) experts and ABM developers. Ideally, these experts themselves understand ABM (if the threshold mentioned above is lowered enough) and its proc and cons. To achieve this hinges upon the next one about education.\

5) At various levels of school education (undergraduate level at the beginning), ABM people may develop (and share if possible) ABM curricula, making the courses available to students. xxx. At the same time, academic researchers and practitioners should start communication with industry, leveraging engineers in computer games.

More?

**References**:

An, L., M. Tsou, S. Crook, B. Spitzberg, J.M. Gawron, and D.K. Gupta. 2015. Space-time analysis: Concepts, quantitative methods, and future directions. Annals of Association of American Geographers 105(5):891-914.

An, L., A. Zvoleff, J. Liu, and W. Axinn. 2014. Agent based modeling in coupled human and natural systems (CHANS): Lessons from a comparative analysis. Annals of Association of American Geographers 104(4):723-745.

An, L., D. López-Carr. 2012. Editorial: Understanding human decisions in Coupled Human-Nature Systems. Ecological Modelling 229(24):1-4.

An, L. 2012. Modeling human decisions in coupled human and natural systems: review of agent-based models. Ecological Modelling 229(24):25-36.

An, L., and J. Liu. 2010. Long-term effects of family planning and other determinants of fertility on population and environment: agent-based modeling evidence from Wolong Nature Reserve, China. Population and Environment 31:427–459.

An, L., G. He, Z. Liang, and J. Liu. 2006. Impacts of demographic and socioeconomic factors on spatio-temporal dynamics of panda habitats. Biodiversity and Conservation 15:2343-2363.

An, L., M. Linderman, J. Qi, A. Shortridge, and J. Liu. 2005. Exploring complexity in a human-environment system: an agent-based spatial model for multidisciplinary and multi-scale integration. Annals of Association of American Geographers 95(1):54-79.

Arthur, W. B. 1999. Complexity and the economy. Science 284: 107-109.

Axelrod, R., and M. D. Cohen. 1999. Harnessing complexity: organizational implications of a scientific frontier. The Free Press: New York.

Bankes, S. C. 2002. Tools and techniques for developing policies for complex and uncertain systems. Proceedings of the National Academy of Sciences 99(3): 7263: 7266.

Bian, L. 1997. Multiscale nature of spatial data in scaling up environmental models. In D. A. Quattrochi and M. F. Goodchild (eds.): Scale in Remote Sensing and GIS, pp. 13-26. Lewis Publishers: New York.

Brown, D. G., D. T. Robinson, J. I. Nassauer, L An, S. E. Page, B. Low, et al. 2008. Exurbia from the bottom-up: Combining empirical observations with agent-based modeling. GeoForum 39(2): 805-818.

Chen, X., A. Viña, A. Shortridge, L. An, and J. Liu. 2014. Assessing the effectiveness of payments for ecosystem services: an agent-based modeling approach. Ecology & Society. 19(1):7 http://dx.doi.org/10.5751/ES-05578-190107

Chen, X., F. Lupi, L. An, R.Sheely, A. Viña, J. Liu. 2012. Modeling the effects of social norms on enrollment in payments for ecosystem services. Ecological Modelling 229(24):16-24.

Chin, A., L. An, J. Florsheim, L. Laurencio, R. Marston, A. Parker, G. Simon, and E. Wohl (in press). Feedbacks in human-landscape systems: lessons from the Waldo Canyon Fire of Colorado, USA. Geomorphology.

Couclelis, H. 2002. Why I no longer work with agents: A challenge for ABMs of human-environment interactions. In LUCC Report Series, eds. D. C. Parker, T. Berger, and S. M. Manson. Bloomington, IN.

Crawford, T. W., J. P. Messina, S. M. Manson, and D. O'Sullivan. 2005. Complexity science, complex systems, and land-use research. Environment and Planning B 32(6): 792-798.

Deadman, P, D. Robinson, E. Moran, and E. Brondizio. 2004. Colonist household decision-making and land-use change in the Amazon rainforest: An agent-based simulation. Environment and Planning B 31: 693-709.

Eliassen, S., B. S. Andersen, C. Jørgensen, and J. Giske. 2016. From sensing to emergent adaptations: Modelling the proximate architecture for decision-making. Ecological Modelling 326:90–100.

Eliassen, S., C. Jørgensen, M. Mangel, J. Giske, and A. E. and E. M. C. Whitlock. 2009. Quantifying the Adaptive Value of Learning in Foraging Behavior. The American Naturalist 174 (4):478–489.

Evans, T. P., and H. Kelly. 2004. Multi-scale analysis of a household level agent-based model of landcover change. Journal of Environmental Management 72: 57-72.

Filatova, T., P.H. Verberg, D.C . Parker, and C.A. Stannard. 2012. Spatial agent-based models for socio-ecological systems: Challenges and prospects. Environmental Modelling & Software 45: 1-7.

Gimblett, H. R. 2002. Integrating geographic information systems and agent-based technologies for modeling and simulating social and ecological phenomena. In Integrating geographic information systems and agent-based techniques for simulating social and ecological processes, ed. H. R. Gimblett, 1-20. New York: Oxford University Press.

Grimm, V., U. Berger, D. L. DeAngelis, J. G. Polhill, J. Giske, and S. F. Railsback. 2010. The ODD protocol: A review and first update. Ecological Modelling 221 (23):2760–2768.

Grimm, V., U. Berger, F. Bastiansen, S. Eliassen, V. Ginot, J. Giske, J. Goss-Custard, T. Grand, S. K., Heinz, G. Huse, A. Huth, J. U. Jepsen, C. Jørgensen, W. M. Mooij, B. Müller, G. Pe’er, C. Piou, S. F. Railsback, A. M. Robbins, M. M. Robbins, E. Rossmanith, N. Rüger, E. Strand, S. Souissi, R. A. Stillman, R. Vabø, U. Visser, and D. L. DeAngelis. 2006. A standard protocol for describing individual-based and agent-based models. Ecological Modelling 198 (1–2):115–126.

Grimm, V., E. Revilla, U. Berger, F. Jeltsch, W. M. Mooij, S. F. Railsback, et al. 2005. Pattern-oriented modeling of agent-based complex systems: Lessons from Ecology. Science 310(11): 987-991.

Giske, J., S. Eliassen, Ø. Fiksen, P. J. Jakobsen, D. L. Aksnes, M. Mangel, and C. Jørgensen. 2014. The emotion system promotes diversity and evolvability. Proc. R. Soc. B 281 (1791):20141096.

Heppenstall, A.J., A.T. Crooks, L.M. See, and M. Batty. 2012. Agent-Based Models of Geographical Systems. Berlin: Springer.

Irwin, E.G., and J. Geoghegan. 2001. Theory, data, methods: developing spatially explicit economic models of land use change. Agriculture, Ecosystem &. Environment 85: 7-23.

Kugler, T. A., D. Van Riper, S. M. Manson, D. A. Haynes II, J. Donato, and K. Stinebaugh. 2015. Terra Populus: Workflows for Integrating and Harmonizing Geospatial Population and Environmental Data. Journal of Map and Geography Libraries (Accepted, in press).

Larkin, D., and G. Wilson. 1999. Object-oriented programming and the Objective-C language. Cupertino, CA: Apple Computer, Inc.

Levin, S.A. et al. 2013. Social-economic systems as complex adaptive systems: Modeling and policy implications. Environment and Development Economics 18(2): 111-132.

Levin, S.A. 2012. Ecological resilience and robustness. Encyclopedia Britannica. Available from: http://www.britannica.com/EBchecked/topic/1919092/ecological-resilience.

Liu, J., T. Dietz, S. R. Carpenter, M. Alberti, C. Folke, E. Moran, et al. 2007. Complexity of coupled human and natural systems. Science 317: 1513-1516.

Liu, Y.Y., Padmanabhan, A., and Wang, S. 2015. CyberGIS Gateway for Enabling Data-Rich Geospatial Research and Education. Concurrency and Computation: Practice and Experience, 27(2): 395-407.

Malanson, G.P., Y. Zeng, and S. J. Walsh. 2006. Complexity at advancing ecotones and frontiers. Environment and Planning A 38: 619-632.

Manson, S. M., J. Shannon, S. Eria, L. Kne, K. R. Dyke, S. Nelson, L. Batra, D. Bonsal, M. Kernik, J. L. Immich, and L. Matson. 2014. Resource needs and pedagogical value of web mapping for spatial thinking. Journal of Geography 113 (3): 107-117.

Manson, S. M. 2013. Public Cyber-Infrastructure for Spatial Analysis. Latin American Studies Association Forum 44 (1): 6-8.

Manson, S. M., L. Kne, K. Dyke, J. Shannon, and S. Eria. 2012. Using eye tracking and mouse metrics to test usability of web mapping navigation. Cartography and Geographic Information Science 39 (1): 48-60.

Manson, S. M., L. Kne, and F. Harvey. 2015. U-Spatial: Support for research and teaching at the spatial university. In STEM and GIS in Higher Education. D. Cowen (ed). Redlands, CA: ESRI Press (Forthcoming).

Manson, S. M. 2002. Calibration, verification, and validation. In LUCC Report Series, eds. D. C. Parker, T. Berger, and S. M. Manson. Bloomington, IN.

Manson, S. M. 2001. Simplifying complexity: a review of complexity theory. Geoforum 32: 405-414.

Messina, J. P., and S.J. Walsh. 2005. Dynamic spatial simulation modeling of the population – environment matrix in the Ecuadorian Amazon. Environment and Planning B: Planning and Design 32(6): 835-856.

National Research Council (NRC). 2014. Advancing Land Change Modeling: Opportunities and Research Requirements. National Academies Press: Washington, D.C.

Ostrom, E. 2009. A general framework for analyzing sustainability of social-ecological systems. Science (2009) 35: 419-22.

O'Sullivan, D. and S. M. Manson. 2015. Do physicists have ‘geography envy’? And what can geographers learn from it? Annals of the Association of American Geographers 105 (4): 704-722.

O’Sullivan, D., T. Evans, S. Manson, S. Metcalf, A. Ligmann-Zielinska, and C. Bone. 2016. Strategic directions for agent-based modeling: avoiding the YAAWN syndrome. Journal of Land Change Science 11(2): 177-187.

Parker, D. C., B. Entwisle, R. R. Rindfuss, L. K. VanWey, S. M. Manson, E. Moran, L. An, P. Deadman, T. Evans, M. Linderman, and G. Malanson. 2008. Case studies, cross-site comparisons, and the challenge of generalization: comparing agent-based models of land-use change in frontier regions. Journal of Land Use Science 3(1):41-72.

Parker, D. C., S. M. Manson, M. A. Janssen, M. J. Hoffmann, and P. Deadman. 2003. Multi-agent systems for the simulation of land-use and land-cover change: A review. Annals of the Association of American Geographers 93 (2):314–337.

Portugali, J. 2006. Complexity theory as a link between space and place. Environment and Planning A 38(4): 647-664.

Railsback, S.F, and V. Grimm. 2011. Agent-Based and Individual-Based Modeling: A Practical Introduction. Princeton, NJ: Princeton University Press

Robbins, M. M. Robbins, E. Rossmanith, N. Rüger, E. Strand, S. Souissi, R. A. Stillman, R. Vabø, U. Visser, and D. L. DeAngelis. 2006. A standard protocol for describing individual-based and agent-based models. Ecological Modelling 198 (1–2):115–126.

Rindfuss, R. R., B. Entwisle, S. J. Walsh, L. An, D. G. Brown, P. Deadman, T. P. Evans, et al. 2008. Land use change: complexity and comparisons. Journal of Land Use Science 3(1):1-11.

Tang, W., Bennett, D.A., and Wang, S. 2011. A parallel agent-based model of land use opinions. Journal of Land Use Science, 6(2): 121-135.

Tang, W. and Bennett, D.A.. 2011. Parallel agent-based modeling of spatial opinion diffusion accelerated using Graphics Processing Units. Ecological Modelling 222(19): 3605–3615.

Walsh, S.J., J.P. Messina, C.F. Mena, G.P. Malanson, and P.H. Page. 2008. Complexity theory, spatial simulation models, and land use dynamics in the Northern Ecuadorian Amazon. Geoforum 39: 867-878.

Wang, N., D.G. Brown, L. An, S. Yang, and A. Ligmann-Zielinska. 2013. Comparative performance of logistic regression and survival analysis for detecting spatial predictors of land-use change. International Journal of Geographic Information Science 27(10):1960-1982.

Wang, S., L. Anselin, B. Bhaduri, , C. Crosby, M. F. Goodchild, Y. Liu, and T. Nyerges. L. 2013. CyberGIS software: A synthetic review and integration roadmap. International Journal of Geographical Information Science 27 (11): 2122-2145.

Wang, S., Y. Liu, and A. Padmanabhan. 2015. Open CyberGIS software for geospatial research and education in the big data era. SoftwareX, DOI:10.1016/j.softx.2015.10.003

Wilson, A.G. 2006. Ecological and urban systems models: some explorations of similarities in the context of complexity theory. Environment and Planning A 38(4): 633-646.

Yu, C., A.M. MacEachren, D.J. Peuquet, and B. Yarnal 2009. Integrating scientific modelling and supporting dynamic hazard management with a GeoAgent-based representation of human–environment interactions: A drought example in Central Pennsylvania, USA. Environmental Modelling & Software 24:1501-12.

Zvoleff, A., and L. An. 2014a. The effect of reciprocal connections between demographic decision making and land use on decadal dynamics of population and land use change. Ecology and Society 19(2):31.

Zvoleff, A., and L. An. 2014b. Analyzing human-landscape interactions: tools that integrate. Special issue on "The Future of Human-Landscape Interactions: Drawing on the Past, Anticipating the Future", (eds: A. Chin, K. Galvin, A. Gerlak, and E. Wohl). Environmental Management 53:94-111.

**APPENDICES**

(To be posted online or/and submitted as complementary materials)

**APPENDIX 1. THE 1ST EMAIL SURVEY (PILOT SURVEY).**

The survey was a precursor of a proposed symposium titled “Agent-Based Modeling 2017: Agent-Based Models in the Social, Human-Environment, and Life Sciences”, which was later funded by the USA National Science Foundation (BCS #1638446). The lead author sent email messages to 27 selected people during August 12 and August 28, 2015, and received 24 replies (Table 1). These 24 scientists comprise the Science Committee of the *ABM’17* Symposium, which has been expanded to include 16 more scholars. Out of the 24 replies, 20 were enthusiastic regarding the proposed effort (See Table 1).

**Pilot Survey Questionnaire** (Sent out as an email message)

As an agent-based model (ABM) developer and user (over 12 years), I am writing to acquire your interest in, and availability for, participating in a potential workshop with its tentative time and place set at 2016 summer or fall, San Diego (with other places possible and partial funding already secured). The workshop goals are to advance complexity science and ABM through leveraging big collaboration, making use of big data, facilitating big computing, building a big ABM community, and producing big scientific advances. The outcome of the workshop may include coauthoring a synthetic paper(s), developing an ABM-related or targeted proposal(s), and facilitating/further solidifying the ABM community and network (for more details see the background below at the end of this email).

I have the following questions for you if you are interested (please Reply this email):

1) Is this workshop (including the goals and expected outcomes) a scientifically significant, necessary pursuit?

2) Are we pursuing the goals at the right timing?

3) Will you be able to participate in the workshop(s)?

4) What time would be good for you (please check all that are good to you)?

Five time options (skipped for brevity)

5) Are you willing to participate in the related proposal or ABM community/network development?

Please feel free to email me should you have questions. Thank you very much for your time in considering this invitation. For my background, visit <http://complexities.org/>.

**Background** (attached in the Pilot Survey)

As a major, powerful tool in complexity science as well as in understanding various systems (e.g., land use land cover change (LULCC) systems, coupled human and natural (CHANS) systems), agent-based models have been widely developed and employed in various domains such as ecology, epidemiology, geography, land change science, political science, and sociology. The power of ABMs lies in their capabilities to represent (hyper)local detail (e.g., individual-level data, activity, and decision-making), heterogeneity, nonlinearity, and feedback. Furthermore, ABM has been demonstrated to be very useful in integrating data and models across multiple disciplines and scales.

However, the increasing need to deal with big data (e.g., simulating a huge number of agents within an environment represented based on high spatial and temporal resolutions) has posed big challenges to ABM developers. Existing ABMs are on largely (with few exceptions that use distributed, parallel computing) a PC basis, lacking the capacity to facilitate high performance computing. Also scientists have developed ABMs in various contexts, they used different platforms, languages, or standards that pose difficulty to compare and validate model structures (often with varying levels of model detail and sophistication) and findings. In general, a variety of ABMs were developed on an ad hoc basis, lacking transparency and reusability. Equally (if not more) importantly, the ABM community faces challenging questions about the justification of developing ABMs (e.g., what unique, scientifically robust insights can we obtain from ABM compared with other approaches?). We are also in dire need for systematic modules, protocols, better graphical user interfaces (GUIs), or easy-to-use (e.g., programming free) platforms that enable us to express the relevant concepts and rules (even though some preliminary advances are already in place, e.g., the ODD protocol by Grimm et al. 2006, 2010). Other difficulties about ABM scalability, generalizability, and model validation also beset ABM modelers. All these difficulties become more challenging when the user is a novice (e.g., due to the relatively sharp learning curve of programming in ABM).

Given the above needs and challenges in complexity science (ABM in particular), we plan to submit a proposal to NSF for holding one or two workshops largely in the summer or fall of 2016. This workshop(s) will aim at seeking insights from a number of stellar scientists like you with background from multiple disciplines. Our goals are: 1) summarizing the status quo and future directions of ABM; 2) discussing the methodology to synthesize existing ABMs—e.g., developing reusable modules, building easy-to-use platforms; and 3) mapping out innovative means to standardize the development, verification, validation, interpretation, and application of ABMs.

Expected outcomes: 1) A synthetic paper that aims at a prestigious journal such as PNAS; 2) one or more proposals that aim to advance complexity/sustainability science through leveraging big collaboration, making use of big data, facilitating big computing, starting to build a big ABM community, and producing big scientific advances; 3) engage broader communities to innovate and sustain ABM.

**Pilot Survey Results**

The majority (92%) replied that the workshop would be scientifically significant and the time was right for it, even urgent, that they would wish to participate (96%), and that most of the replies indicated the months when they can participate.

In addition to the aforementioned supportiveness, some comments directly corroborated the significance of the workshop, facilitated our establishment of four tentative topics (Table 2), and/or convinced us the potential usefulness of our proposed symposium. For instance, as pointed by one invitee, ABM (and the broader complexity science) activities are much more coordinated in Europe than in USA: “Probably one of the challenges is that there are various attempts and initiatives to get towards an ABM community, but because those initiatives don’t coordinate a real functioning community is not taking off in the USA (in contrast to Europe). For that reason it would be good for me to join your workshop”. Another invitee suggested that “I think that more targeted workshops on some of the identified challenges will be more useful as they have the potential to go a bit further while otherwise we would come up with a perspective paper listing issues that we are already aware of. We now need to solve these issues and make plans for this”—Note that one of the four tentative topics (below), i.e., modeling human decisions, comes from this invitee’s suggestion.

And also one invitee indicated that “Yes, 100%. If you see our Digging into Data grant (http://wici.ca/new/research/digging-into-data-did-research/) it fall in the last priorities squarely. This grant was small and ends soon, hopefully with the production and presentation of a prototype, and we would love to get feedback and collaborate on next steps, as we hope to expand this as an extension to the ComSeS platform”.

Table S1. List of People Surveyed in 2015 through 2017



The people with \* were not included in the 1st survey (i.e., pilot survey).

**APPENDIX 2. THE 2ND EMAIL SURVEY**

**Survey questionnaire**

This survey consists of five questions for two groups of people, and you may answer three of them (either Q1, Q2, and Q3, or Q1, Q4, and Q5 depending on the group you perceive you are in). After opening this file, please write your input after each question, and save with your last name as prefix (e.g., Smith-Survey-questions.docx). Once complete, please send it to [abm17@complexities.org](mailto:abm17@complexities.org). For questions that do not apply, put “N/A” under the related question.

Term definition: 1) ABM represents Agent-Based modeling (or models). 2) ABM users/contributors refer to people who either use or have used ABM in their research or other types of work, or may provide domain knowledge or advice on the science and technology of ABM. 3) ABM developers refer to people who design the concept model, write the related code, and verify and validate the code in their work. If you both develop and use ABM, you may answer all questions in both sections

**Q1.** My domain(s) of research is (please circle all that apply to you): 1) human-environment or geographical sciences; 2) life sciences; 3) social sciences; 4) Information or computer sciences; 5) Other (specify): \_\_\_\_\_1 and 3. I’m more of a user than a developer, though I have certainly written some code.\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

**Group I. ABM users/contributors** [Skip Q2 and Q3 below if you consider you belong to Group II only]

**Q2.** In what area(s) do you think ABM is most useful/powerful to address research questions in your domain?

**Q3.** Please list the issues or challenges that ABM could help with, but which are not sufficiently / well addressed in order to advance ABM-relevant research in your domain (or specifically list the barriers that prevent you from using ABM).

[Optional] In your opinion, how can these issues or challenges be addressed?

**Group II. ABM developers** [Skip Q4 and Q5 below if you consider you belong to Group I only]

**Q4.** Please list the bottleneck challenges or issues affecting ABM development that need to be addressed.

**Q5.** If you had no budgetary and/or personnel constraints, how would you go about addressing challenges/issues mentioned in Q4?

[Optional] Other comments or suggestions (anything related to ABM; open-ended):

**Survey results**

The detailed results are posted at <http://complexities.org/ABM17/wp-content/uploads/2017/04/Survey-summary-02-08.pdf>. Below we provide results that are shared by three or more people.

Q2. In what area(s) do you think ABM is most useful/powerful to address research questions in your domain?

Feedback and interactions (Barton, Deadman, Jankowski, KLacasse, Liu, Manson, Nara, Radchuk, Robinson, Turner, Walsh)

Complex/adaptive systems (Nara, Robinson, Schlueter, DP, Turner, Zellner)

Human-environment system (LU) (Barton, Clarke, Deadman, Liu, Manson, Walsh)

Q3. Please list the issues or challenges that ABM could help with, but which are not sufficiently / well addressed in order to advance ABM-relevant research in your domain (or specifically list the barriers that prevent you from using ABM).

Massive ABM (Barton), # of agents (Barton, Keith), big data ABM (Heppenstall)

Model validation (Clarke; Evans; Heppenstall; Tesfatsion)

Calibrate and parameterize ABM (Clarke; Evans; Heppenstall)

Model uncertainty and nonlinearity (Clarke; Deadman; Walsh)

Q4. Please list the bottleneck challenges or issues affecting ABM development that need to be addressed.

Short of micro data for model calibration / parameterization (Axtell; Heppenstall; Nara; Radchuk)

Code transparency and reusability (Barton; Dou; Janssen; Radchuk; Schlueter; Parker; Tang)

Model calibration and validation (Janssen; Schlueter; Walsh: process vs. pattern)

Q5. If you had no budgetary and/or personnel constraints, how would you go about addressing challenges/issues mentioned in Q4?

Organize ABM workshops/programing training for social/biological scientists (Janssen; Radchuk; Robinson)

**APPENDIX 3. THE 3rd EMAIL SURVEY**

**Survey Questionnaire**

Q1. According to the survey performed in 2016, we have identified six topics that will be discussed in breakout sessions and (very likely) advance to paper writing. Please rank them based on the level of desirability to you (1 the most desirable, 2 desirable,…, 6 the least desirable) and put the rank number in brackets:

a. Human decision making in ABM [ ]

b. ABM code reusability and transparency [ ]

c. Model validation and verification [ ]

d. Big data high performance ABM [ ]

e. Integrated human-environment ABMs [ ]

f. Methodological issues of spatially explicit ABMs [ ]

Q2. In consideration of the above list, please identify specific issues that you want to discuss at the ABM 17 symposium (no space limit):

Q3. We will have a set of poster presentations from junior ABM scholars, for which we hope you can serve as a judge. Please rank the poster domains below in the order of how confident you are about judging them (1 for most appropriate, 2 for appropriate, 3 for Okay, and NA for not appropriate or not available) and put the rank number in brackets:

a. Life science [ ]

b. Social science [ ]

c. Human-environment science [ ]

Q4. Please send us a list of recommended ABM related readings (no limit to the max number), including your own or other people’s papers, book chapters, reports, etc.

Below are optional questions that may help us better organize the symposium

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Q5a. Do you (including your group or students you advise or supervise) have a runnable ABM model, including both code, data (Okay if you want to modify the data to meet the IRB requirements), and documentation, which can be shared to the ABM 17 symposium?

1. Yes 2. No 3. Not sure for now

Q5b. (If you choose Yes in Question 5a) In what language or platform was the model developed?

Q6 (Optional) Is there any food you would like to avoid?

Q7. (Optional) Any other constraints that you want us (the ABM 17 organizing committee) to consider?

Please save your survey in this format: Last-name-survey#2.docx, e.g., Smith- urvey#2.docx, and email it to abm17@complexities.org by February 28.

Q8. Position paper (sent out in a separate email message)

**Title:**

**Name and affiliation**

[0.5 ~ 2 pages]

Hint: The position paper is flexible in content and style, which might include (but are not limited to):

1) your area(s) of interest or insight into ABM;

2) why (in what areas) you like or dislike ABM;

3) your potential plan or next steps that are related to ABM;

4) what you envision the ABM community to accomplish within the next 2-5 years; or

5) what you expect the ABM 17 symposium to accomplish (specific outcomes the ABM 17 science committee should develop before, during, and after the symposium; the strategy to achieve these outcomes).

Please save your paper in this format: Last-name-position\_paper.docx, e.g., Smith-posititon\_paper.docx, and email it to abm17@complexities.org by March 10 if possible.

**Survey results**

The results are posted at <http://complexities.org/ABM17/resources/> (click on 2nd Survey). Below summarized results for Questions 1, 2, and 3 are displayed.

Q1. According to the survey performed in 2016, we have identified six topics that will be discussed in breakout sessions and (very likely) advance to paper writing. Please rank them based on the level of desirability to you (1 the most desirable, 2 desirable,…, 6 the least desirable) and put the rank number in brackets:

  a. Human decision making in ABM [ ]

b. ABM code reusability and transparency [ ]

c. Model validation and verification [ ]

d. Big data high performance ABM [ ]

e. Integrated human-environment ABMs [ ]

f. Methodological issues of spatially explicit ABMs [ ]

Figure S1. The topics of interest and expertise

Q2. In consideration of the above list, please identify specific issues that you want to discuss at the ABM 17 symposium (no space limit):

Figure S2. The specific issues or themes of interest

Q3. We will have a set of poster presentations from junior ABM scholars, for which we hope you can serve as a judge. Please rank the poster domains below in the order of how confident you are about judging them (1 for most appropriate, 2 for appropriate, 3 for Okay, and NA for not appropriate or not available) and put the rank number in brackets:

a. Life science [ ]

b. Social science [ ]

c. Human-environment science [ ]

Figure S3. Areas of expertise of ABM 17 Science Committee