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Current Opinion in Environmental Sustainability

Scale and the representation of human agency in the modeling of agroecosystems

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Human agency is a critical determinant of the dynamics of agroecosystems. However, the manner in which agency is represented within different approaches to agroecosystem modeling is largely contingent on the scales of analysis and the conceptualization of the system of interest. While appropriate at times, narrow conceptualizations of agroecosystems can preclude consideration for how agency manifests at different scales, thereby marginalizing processes, feedbacks, and constraints that would otherwise affect model results. Modifications to the existing modeling toolkit may therefore enable more holistic representations of human agency. Model integration can assist with the development of multi-scale agroecosystem modeling frameworks that capture different aspects of agency. In addition, expanding the use of socioeconomic scenarios and stakeholder participation can assist in explicitly defining context-dependent elements of scale and agency. Such approaches, however, should be accompanied by greater recognition of the meta agency of model users and the need for more critical evaluation of model selection and application.

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Current Opinion in Environmental Sustainability 2015, **14**:xx–yy

This review comes from a themed issue on **Open issue**

Edited by **Eduardo S Brondizio, Rik Leemans** and **William D Solecki**

Received 14 December 2014; Revised 15 May 2015; Accepted 23 May 2015

http://dx.doi.org/10.1016/j.cosust.2015.05.010

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Introduction

The implications of global change for the sustainability of global and regional agroecosystems and food security continue to be a priority research and policy concern [1]. This concern arises in part from the complexity of agroecosystems, which poses significant challenges to predicting their responses to multiple driving forces. Agroecosystems can be characterized as socioecological systems with dynamically interacting, multi-scaled socioeconomic and ecological subsystems [2]. While physical, biological, and ecological sciences provide powerful tools for understanding changes in the Earth system as well as the physiological response of crops and livestock to those changes, human interventions are a significant source of complexity and uncertainty in the behavior of agroecosystems. Few, if any, aspects of agroecosystems are unaffected by human agency — the capacity of actors (i.e., individuals, organizations, and institutions) to act, directly or indirectly, to affect change [3•,4,5]. Agency can manifest in different modes: individual decision-making; proxy decisions made on behalf of others; and collective action based on pooled knowledge and resources [4]. It also influences, and is influenced by, the structure of society and the interactions among its institutions that enable or constrain the capacity to act.

A common characteristic of agroecosystems is the dependence of their dynamics and behavior on scale [6••,7]. Therefore, diagnosing and predicting socioeconomic and ecological influences on agroecosystem processes and outcomes are facilitated by conceptualizing, observing, and modeling the system at scales that are relevant to the questions that are being asked [8,9••]. Cash *et al.* [10, pg. 2] define scale as '*the spatial, temporal, quantitative, or analytical dimensions used to measure and study any phenomenon*.' This definition acknowledges the importance of spatial and temporal scales to the understanding of socioecological systems, but also recognizes that a broader range of scales can be applied in systems analysis such as institutions, networks, or knowledge. In addition, each scale is composed of multiple levels, which represent the units of analysis [10]. For example, knowledge relevant to agroecosystems can be local and contextual, such as a specific management practice for a particular location and crop, or global and general, such as awareness that agricultural production is influenced by environmental conditions of climate, topography, and soils.

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Consistent with such definitions, a broad range of scales and associated levels relevant to agroecosystems have been identified in the literature (Table 1). These represent useful points of entry for agroecosystem analysis. Human agency, like many other system properties, varies across the levels of these scales, from individual decision-making by actors at specific point in time and space to the more aggregate consequences of complex governance systems composed of diverse actors with agency at multiple levels [11]. Consideration of the interactions between agency and scale is therefore an important component of understanding the response of agroecosystems to global change in the Anthropocene [12]. The objective of this paper is to examine the interactions between scale and human agency reflected in various modeling tools currently available to researchers in assessing the responses of agroecosystems to different driving forces. In so doing, the paper identifies key elements of scale that are relevant for addressing different questions regarding the sustainability of agroecosystems, reflects on how well existing models are positioned to inform those questions, and identifies potentially useful advances to enhance the capacity for modeling of agroecosystem dynamics.

Scale and human agency

Actors associated with agroecosystems have management objectives that they seek to achieve through the implementation of system interventions. Because interventions are an expression of choice, implementation is contingent on agency. However, actors, their objectives, and agency can vary with scale and across the levels of those scales [13,14]. The framing of agroecosystems as multi-scale and/or multi-level therefore provides an analytical lens that aids in identifying important processes and interactions by which agency influences system behavior and outcomes. One immediate implication of such a framing is that attempts to conceptualize or model agroecosystems as discrete, closed systems may result in biased insights or mask important consequences [3•]. The multi-scaled, multi-level nature of agroecosystems creates the potential for significant spatial and temporal teleconnections to arise from human agency [15]. In fact, current challenges associated with the sustainable management of agroecosystems to support livelihoods, food security, and ecological integrity are increasingly associated with such complex dynamics where actions in one place and time have consequences elsewhere [16••,17].

Two examples from the literature can be used to illustrate the scale complexity inherent in current challenges associated with the management of agroecosystems. First, U.S. federal policies incentivizing bioenergy in pursuit of energy security have led to marked increases in corn production. While beneficial for individual producers [18], rapid growth in ethanol production has led to concerns regarding competition for the use of corn as food, fiber, and fuel [18,19]. The rate of growth in corn use for ethanol has risen disproportionately to the growth in corn for other uses [20]. Competition between food and fuel has been exacerbated during periods of declining yields associated with droughts or other climatic stresses [20]. As a case-in-point, during the U.S. 2012 drought, corn and ethanol prices rose to their highest levels in a decade [20]. Meanwhile, expanded corn production has also been linked to adverse externalities for natural ecosystems [21]. Hence, agency at the national level has had direct implications for decision-making at the farm level in terms of land use and crop selection. It has also had indirect implications at the international level with respect to perceived adverse impacts on land use change, greenhouse gas emissions, food security, and equity [18,19,22–24].

Table 1

Scales and levels relevant to the analysis of agroecological systems

Type of scale	Examples of levels	Selected references
Spatial	• local → regional → national → global • centimeter^2 → meter^2 → kilometer^2	[34,69,76]
Temporal	• hourly → daily → monthly → annual → decadal → millennial	[34,69]
Jurisdictional	• cities → counties → states/provinces → nations → multi-national → international	[34,59,76]
Biophysical	• organism → population → community →ecosystem → Earth system	[34,59,77,78]
Economic	• micro → macro	[59,69,77]
Institutional	• bounded → unbounded • small government → big government • operating rules → policies → laws/regulations → constitutions	[34,57,77,78]
Management	• tasks → projects → practices → strategies	[34,69]
Risk	• negligible → manageable → intolerable	[14,78,79,80•,81]
Ethical	• fair → unfair • equal → unequal	[82,83]
Developmental	• under-developed → developing → rapidly developing → developed	[3•,84]
Networks	• family → kin → society → trans-society	[14,31,69]
Knowledge	• specific/contextual → general/universal	[10,78,85]

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A second example involves the externalities associated with interactions between sub-surface tile drainage and chemical fertilizer application — management practices that expanded in the U.S. Midwest during the 20th century, the former as a solution for water logged soils and the latter as a remedy for declining soil quality. At the farm level, these practices resulted in increased productivity. However, these combined practices delivered water with high-nutrient loads downstream, which contributed to water quality impairment including the 'dead zone' in the Gulf of Mexico [25,26]. Because the Mississippi River and Gulf of Mexico fall under the jurisdiction of nine federal agencies and Mexico, as well as the governments of ten bordering states [27], awareness of the dead zone triggered action across diverse institutions and actors, with subsequent feedbacks to agricultural practices on farms. Such 'dead zones', however, are not only an agricultural issue, but also an ecological one that affects other actors, sectors, and livelihoods [25,28]. A holistic view of the relationship between agricultural practices and the 'dead zone' can be deconstructed to identify the multiple scales in operation — spatial, temporal, institutional, management — and the characteristic levels of each (Figure 1). Although some scales are difficult to describe using a strict hierarchical framing [29], for each scale a contrast can be made between micro levels that are local and/or immediate and macro levels that are aggregations of subsidiary levels. Although discrete elements of the system can be identified and analyzed, it is the interactions across different scales and levels that create teleconnections and indirect effects that drive system outcomes [30].

While such dependency can be readily recognized and diagnosed within historical case studies, prognostic analyses with *a priori* specification of scale-dependent agency pose more formidable challenges. Prognostic models represent important tools for investigating the dynamic responses of agroecosystems to different factors and their interactions [31]. The processes in these models, including human agency, are generally, and by and large appropriately, designed to address a relatively bounded problem and therefore are developed to incorporate a limited number of scales and levels. This makes the conceptualization of the system of interest a critical consideration in the development and application of models [32,33]. For example, a point-based crop model may be sufficient to investigate the direct effects of climate variability and change on crop yields for an individual farm. However, in practice, the consequences of such effects are mediated by a range of other exogenous factors such as markets, farm management, and policies, which link outcomes at the farm level to a broad range of social institutions. Meanwhile, using models to explore broader themes of food security requires the conceptualization of agroecosystems as complex systems,

Figure 1

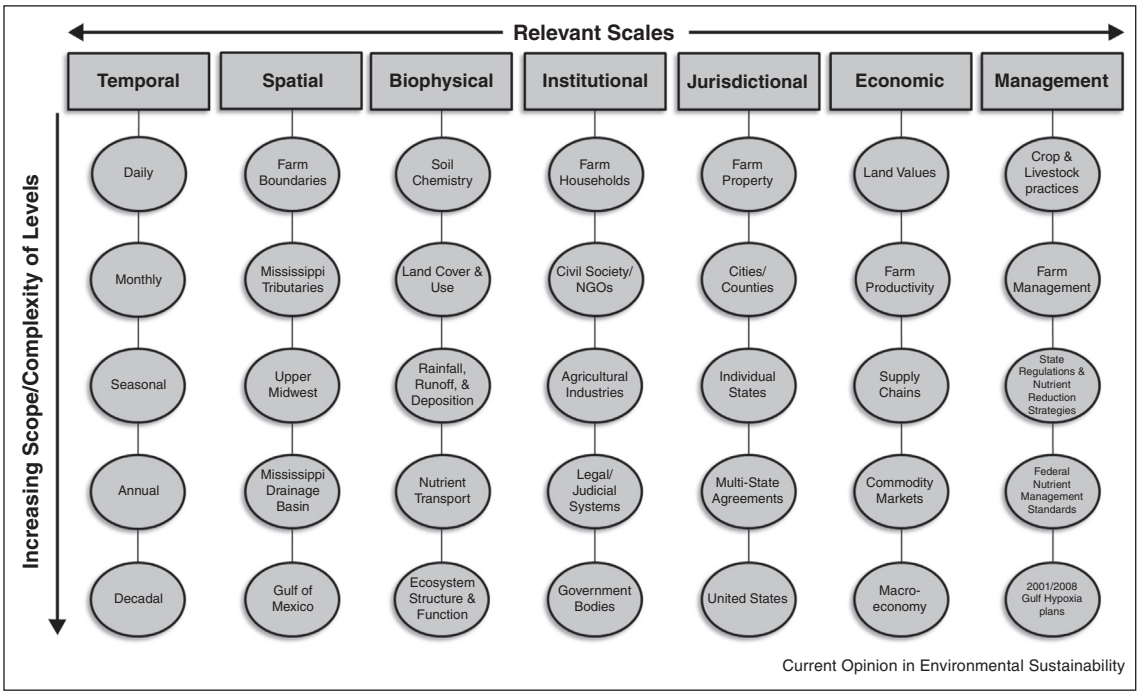

Illustration of the various scales and associated levels that can be used in the analysis of the relationship between agricultural practices in the Mississippi drainage basin and the Gulf of Mexico 'dead zone'. Scales and levels are based on Table 1 and relevant scientific and policy literature [25,108–112].

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which significantly increases the demands with respect to scales and levels that are represented, processes that are included, and data needs. Adapting models to represent such complexity remains challenging [34].

Representation of agency within agroecosystem models

The complexity of agroecosystems, the scope of human interest in these systems, and the breadth of relevant scientific disciplines are all reflected in the diversity of available tools for agroecosystem modeling (Table 2). This diversity reflects model development processes that focus on addressing specific questions for specific scales and levels rather than holistic, systems-based analysis [30,35]. Some models, such as crop simulation models (Table 2) are designed for applications at the level of individual fields, over time periods of a cropping season or a very few years, and focus almost exclusively on the biophysics of plant growth and productivity. Others, such as some integrated assessment models (IAMs; Table 2), can be global in their spatial extent, use and generate data over multi-decadal time periods, and represent the

Table 2

Scales and agents associated with agroecosystem models including extent to which agency is implicitly or explicitly represented

Modeling approach	Relevant scales of modeling	Actor	Implicit or explicit agency	Examples
Production-function				
Statistical yield models	• Spatial • Temporal • Biophysical • Jurisdictional	• None	• N/A	[86]
Process-based crop simulators	• Spatial • Temporal • Biophysical • Management	• Farmer	• Implicit	[36,37,38]
Crop distribution models	• Spatial • Temporal • Biophysical	• None	• N/A	[54]
Economic models				
Partial equilibrium models with agricultural sector	• Spatial • Temporal • Biophysical • Economic • Jurisdictional • Institutional	• Markets	• Explicit	[37,87,88,89]
General equilibrium models	• Spatial • Temporal • Economic • Jurisdictional • Institutional	• Markets	• Explicit	[90,91]
Input/output models	• Spatial • Temporal • Economic • Jurisdictional • Institutional	• None	• N/A	[92,93]
Ricardian analysis models	• Spatial • Temporal • Biophysical • Economic • Management	• Farmer	• Implicit	[40,41]
Bio-economic farm models	• Spatial • Temporal • Biophysical • Economic • Management	• Farmer	• Implicit	[62,94,95]
Integrated assessment models (IAM)				
Global IAMs	• Spatial • Temporal • Biophysical • Economic • Jurisdictional • Institutional • Management • Developmental	• Markets • Policy-makers	• Implicit	[96•,97,98,99]

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Table 2 (*Continued*)

Modeling approach	Relevant scales of modeling	Actor	Implicit or explicit agency	Examples
Regional IAMs	• Spatial • Temporal • Biophysical • Economic • Jurisdictional • Institutional • Management	• Markets • Policy-makers • Other stakeholders	• Explicit	[71••,72••,100]
Decision models				
Agent-based models	• Spatial • Temporal • Biophysical • Economic • Institutions • Management • Networks • Risk • Ethical	• Farmer • Markets • Other stakeholders	• Explicit	[45,46,47,48,101,102]
Non-agent-based models	• Spatial • Temporal • Biophysical • Management • Ethical	• Farmer • Other stakeholders	• Implicit & Explicit	[103•,104,105]
Supply chain optimization models	• Spatial • Temporal • Economic • Management • Networks	• None	• N/A	[106,107]
Risk models				
Catastrophe loss models	• Spatial • Temporal • Biophysical • Economic • Jurisdictional • Institutional • Risk	• None	• N/A	[80•,81]

contribution of agriculture as a sector of the global economy. The result is a large and diverse 'toolbox' of models. However, each individual model generally targets a limited set of questions that ultimately influence the range of agroecosystem scales and levels that are prioritized and represented within a model.

With regard to agency, models vary with respect to who the actor is — from individual farmers to international corporations or other aggregated economic entities — and in how that agency is represented — from explicit decision rules that are introduced exogenously to implicit processes. This can be readily explored by examining how agency is represented within different types of models (Table 2). At the level of individual fields and farms, the actor is generally conceptualized as the individual farmer or land owner. Agency at this level is very much implicit in crop simulation models like APSIM [36], DSSAT [37], and EPIC [38] in the sense that there are specified farm operations that presume an actor, but there are no explicit decision rules or adjustments in operations in response to dynamically changing conditions. Hence, actors in these types of models have been characterized as 'dumb' [39] or 'naïve' [40]. In contrast, the implicit actors in empirical Ricardian models (which use rent or land values as an analysis endpoint rather than crop yields), have been described as clairvoyant because they are assumed to respond optimally in order to maximize production [40,41]. Yet, these are idealized assumptions that do not capture the complexities of agency at spatial and temporal scales of individual farms and farmers [40], nor do they represent responses triggered by agency at other levels or scales.

Agent-based and behavioral models are designed to address such limitations by explicitly simulating the decision-making process of individual or small groups of farmers in response to environmental, economic, and institutional constraints (Table 2) [42–44]. The Mathematical Programming-based Multi-Agent Systems (MP-MAS), for example, is an agent-based approach with a strong foundation in microeconomics and farm management theory and optional modules for simulating biophysical dynamics [45]. Land-use and operational decision-making by one or more individual actors are explicitly represented as responses to biophysical

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conditions, economic markets, and social networks for innovation diffusion. Bert *et al.* [46] take a similar approach in which individual farmers make choices among specified options based upon environmental and economic conditions according to explicit decision-making rules. Models such as CATCHSCAPE [47] and SYPRIA [48] extend such approaches by explicitly modeling the behavior of other actors such as water resource managers, non-agricultural households, and industries [45]. Meanwhile, behavioral models (e.g., [49,50•]) explicitly represent the psychology and cognitive reasoning of decision-making by individuals. Results generated by agent-based models at the individual farm level can be subsequently aggregated to represent agroecosystem dynamics and outcomes at higher levels of geographic organization. However, challenges remain with respect to capturing non-linear dynamics, teleconnections, and changes in socioeconomic systems [51,52].

Some models use aggregate geographic levels as a starting point. As a result, agency shifts from the individual and groups of individuals to collective, holistic actors including regional and national agencies and markets (Table 2). This is often accompanied by more aggregate temporal scaling as decisions shift from near-term, tactical to longer-term, strategic and structural choices [40]. Spatially aggregated empirical models of crop productivity at the regional or national level are often developed using historical data on variations in crop yields and correlations with co-occurring variations in climate (e.g. [53,54]). The data used in these models are most often available for subnational politically-defined districts (e.g., counties in the United States) and the spatial scale of these models is thus the spatial scale of those geo-political units. There is essentially no human agency in these models. While agent-based farm models can be implemented on an agricultural landscape of multiple farms, as that landscape expands spatially to the regional and national level, the explicit simulation of large numbers of agents and their interactions becomes intractable [51].

At the national and international level, the modeling tools which address agriculture are largely macroeconomic models. One type includes national level input–output models (Table 2), for which there is no representation of agency. The actors in the general and partial equilibrium models applied at national and international scales, including IAMs, are highly aggregated, effectively non-decomposable collections of commodity and other market traders. While crop selection, land use, and technology improvements all reflect some degree of implicit decision-making by various actors at different scales and levels [55], these processes are often operationalized as endogenous factors driven by utility maximization. Nevertheless, such models retain the capacity to undertake policy experiments relevant to agroecosystems, such as national energy policies associated with bioenergy production [23].

Limitations of the existing toolkit

Although the existing modeling toolkit for agroecosystems is extensive, a number of shortcomings are evident. First, available tools are often limited with respect to the scales they explicitly represent (Table 2), as well as the levels associated with those scales. Furthermore, levels among scales are generally correlated, such that a focus on higher levels of one scale is accompanied by a similar high level focus at other scales. Although spatial and temporal scales are inherent to environmental modeling, other scales described in the literature as being relevant are not routinely represented. For example, there is little consideration for the role of social institutions apart from the economy. Models favor expert, generalizable knowledge over local, traditional, and contextual knowledge, and therefore may not capture heterogeneity among farms, communities, or regions [3•]. Ethical considerations or exploration of the role of different levels of social networking are often absent, except in the case of agent-based and behavioral models. While such gaps are often by design, missing scales have important implications for the representation of agency. Institutions have a critical role in the development of capacity to implement agroecosystem interventions. Ethics and values are fundamental to choices regarding environmental management and the uptake of different technologies such as bioenergy or genetically modified foods [56]. Different levels of knowledge manifest in agroecosystems, as farm level management practices are strongly influenced by local, contextual knowledge.

Second, models encounter significant challenges not simply with scales, but also with scaling [57]. An obvious case is one of spatial scaling problems, whereby the processes and outcomes modeled at one level are not illustrative of those at other levels. For example, farm level models of agricultural productivity may provide few insights into questions of food security if they do not consider issues of procurement, supply chains, and markets, which are influenced by agency at higher spatial and institutional levels [58]. In particular, an apparent gap exists between the farm level models where individual actors make explicit choices and regional to global models where agency is the aggregate behavior of heterogeneous actors at different levels [59]. Furthermore, while empirical and process-based crop models are common tools for exploring the future implications of global climate change on agricultural production and food security, such tools were not developed for long temporal integrations, in part because they erroneously assume relationships and conditions will remain stationary. Such scaling problems are exacerbated by the aforementioned failure to consider alternative scales of modeling. Practices and outcomes that generate trade-offs among scales or levels are difficult to reconcile without engaging ethical considerations and/or jurisdictional and institutional scales where power to reconcile such trade-offs reside.

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Third, as with any quantitative model, the capacity to represent complex systems and their behavior is contingent on the availability of input data for model variables and processes as well as data for model calibration and validation. Advances in environmental observing systems, computation, and simulation are creating new data sets and data management capabilities. Yet, such advances have not addressed all data needs, and the large data volumes associated with climate, land use, and simulation pose challenges in their own right [60]. These problems are common to multiple types of agroecosystem models. For computational general equilibrium models, improved information is needed regarding biofuel technologies, the economics of forestry enterprises as well as water supply and demand [61]. Meanwhile, in reviewing bio-economic farm models, Janssen and van Ittersum [62] note that the data needs of models can limit their transferability to other geographic locations and problems. The data problem extends beyond simply the availability of information and includes challenges associated with the integration of disparate data, which necessitates consistent units and spatial and temporal levels, as well as compliance with copyright and citation practices [63].

Fourth, there is limited consideration for how human agency in problem framing and the selection of which models to use affect model results and interpretation [64]. Up to this point, agency has been discussed from the perspective of the virtual actors that exist within models themselves. For example, the application of different management practices within a crop model or the optimal selection of crops within an IAM are virtual representations of real world decision-making and behavior. However, except perhaps in the case of agent-based and behavioral models that attempt to simulate actual decision processes and choice, agency within models is largely parameterized — there are, of course, no real actors within models making decisions. Furthermore, the choices that exist within models are invariably an illustrative, constrained set of choices available in the real world [65]. The normative decisions made by model developers and users regarding what response and management options should be included ultimately influence model behavior and the results that are generated. Hence, virtual actors can be juxtaposed against the meta actors — the developers and users of the models. Users make conscious and deliberate choices regarding what models to use, to address specific problems, under a defined set of assumptions.

Toward multi-scaled human agency in agroecosystem modeling

One valuable objective of agroecosystem model development should be to develop models that capture the richness of human agency, both to avoid potential bias in model results as well as to enhance their relevance to decision-making. Various approaches exist for addressing this challenge. As a starting point, boundary critique can be more rigorously applied to better understand the connections between agroecosystem models and the systems they attempt to represent. To this end, the concept of scale as defined here can be used a tool for assessing, articulating, and defining the conceptual foundation and boundaries of a modeling activity. Given the scientific and practical demands for increasingly complex modeling tools that can provide insights regarding socioecological systems, mechanisms for managing that complexity can be beneficial. As illustrated here (Figure 1), explicitly identifying the scales and levels relevant to the development or application of agroecosystem models can assist in identifying their strengths and weaknesses. This information can be used to prioritize model development or data needs and/or to identify model limitations and knowledge gaps that may affect interpretation and use of their results. Furthermore, more explicit use of stakeholders as meta actors in modeling can enhance model legitimacy [66]. Moreover, stakeholders have valuable knowledge, particularly at the local level, with respect to interactions between agency and different scales as well as the scalability of different modeling tools and their assumptions [67]. Therefore, stakeholder participation can assist in model evaluation and therefore model improvement [68].

In addition, greater emphasis on model integration or coupling can be an effective pathway for linking top-down and bottom-up models to incorporate agency across multiple scales and levels [69,70•]. For example, Thomson *et al.* [71••] use a high-resolution version of the EPIC crop model nested in the Global Climate Assessment Model (GCAM) IAM. GCAM provides high level boundary conditions for EPIC in terms of land use and macroeconomic driving forces while EPIC models agricultural productivity for a range of management practices. Such approaches link farm-level production and management to global markets and aggregate agricultural outcomes. However, dynamic agency in modifying farm operations in response to changing conditions is limited and the intermediate levels of scales and agency are not necessarily well-represented. Additionally, some scales of agroecosystems, such as institutions or ethical considerations, lack explicit definition. Hence, exploring other ways of coupling different types of models to capture a broader range of scales and levels may help address such gaps.

An alternative approach is to acknowledge the inherent constraints imposed by models on the representation of agroecosystem scale dynamics and apply models in concert with a broader societal context. To this end, the use of socioeconomic scenarios to define alternative futures that include not only population and economic growth, but also preferences for behaviors, attitudes toward the environment, technological change, adaptation options and capacity can help to create context around models,

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and even influence model parameterization. Scenarios can also assist with scaling challenges by articulating conditions, trends, and agency at multiple levels. For example, the multi-sector RegIS IAM used the UKCIP national socio-economic scenarios which were extended to the regional level [66]. More recently, Harrison *et al*. [72••] applied scenarios for Scotland and the European Union as part of the CLIMSAVE integrated assessment platform. The recent emergence of the next generation global Shared Socioeconomic Pathways represent an opportunity for consistent use of socioeconomic scenarios for IAM and other agroecosystem assessment efforts [73•,74], provided additional investment is made in demonstrating the scalability of those scenarios [74,75].

Conclusions

Models represent valuable tools for understanding the status, potential responses, and fate of agroecosystems. Human agency is a critical factor influencing agroecosystems, yet one that is not comprehensively addressed across the existing modeling toolkit, in part due to the challenges associated with modeling how agency varies with scale. This leaves the insights emerging from agroecosystem models vulnerable to spurious conclusions. Modeling frameworks that emphasize the integration of multiple models that represent multiple scales and levels as well as those that integrate quantitative and qualitative information may be more robust tools for generating scalable insights regarding the dynamics of agroecosystems under global change. Meanwhile, more critical reflection upon the selection and use of models in support of different research objectives and/or societal applications can better enable responsible model use.

Acknowledgements

This research was sponsored by the U.S. Department of Energy, Office of Science, Biological and Environment Research, Integrated Assessment Program under project ERKP719. This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

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