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SPECIAL ISSUE ARTICLE

# Evolving human landscapes: a virtual laboratory approach

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**ABSTRACT**

Different human societies shape landscapes differently. Anthroecology theory explains this long-term differential shaping of landscapes as the product of sociocultural niche construction (SNC): an evolutionary theory coupling social change with ecosystem engineering. The evolutionary mechanisms underpinning this theory cannot be tested without experimental approaches capable of reproducing emergent selection processes acting on the combined suite of cultural, material, and ecological inheritances that determine the adaptive fitness of human individuals, groups, and societies. Agent-based modeling, as a 'generative social science' tool, appears ideal for this. Here we propose an agent-based virtual laboratory (ABVL) approach to generating and testing basic hypotheses on SNC as a general mechanism capable of producing the broadly varied anthroecological forms and dynamics of human landscapes from prehistory to present. While major challenges must still be overcome, a prospective modeling framework specification, guiding questions, and illustrative examples demonstrate clear potential for an ABVL to test predictions of anthroecology theory through generative social simulation.

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**KEYWORDS**
Land-use theory; simulation; geography; coupled human natural systems (CHANS); social-ecological systems (SES); telecoupling

## 1. Introduction

The concept that landscapes coevolve with human societies is at least as old as the disciplines of natural history and geography (e.g. Alexander von Humboldt, in Jackson, 2009; Marsh, 1865). As societies change, they alter the landscapes that sustain them. As environments change, human societies respond through adaptive social processes and by intervening further into landscape processes. This coupling of social, environmental, and landscape change is foundational to land system science (LSS; Meyfroidt, 2015). It is also the basis for theoretical frameworks ranging from social-ecological systems (SES; Walker, Holling, Carpenter, & Kinzig, 2004) to coupled human-natural systems (CHANS; Liu et al., 2013) and the human–environment models of archaeology (Boivin et al., 2016; Butzer, 1982; Kirch, 2005) and human ecology (Dyball & Newell, 2014).

Despite this long history of theoretical work, the call to recognize human societies as a 'great force of nature' that is shifting the Earth system into a new epoch of geologic time, the Anthropocene (Steffen, Crutzen, & McNeill, 2007; Waters et al., 2016) is challenging LSS, SES, and CHANS to develop globally generalizable, mechanistic models of human transformation of landscapes across Earth's land over geologic time (Ellis, 2015; Verburg et al., 2015). Just as natural climate systems have shaped the global patterns of the biomes over evolutionary time, human populations and their use of land, acting as a 'global human climate system', have shaped, over

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millennia, the global patterns of urban, village, cropland, rangeland, and seminatural anthropogenic biomes (anthromes) that now cover most of Earth's land (Ellis, 2015; Ellis & Ramankutty, 2008).

Contemporary LSS, SES, and CHANS modeling approaches are increasingly capable of simulating coupled social-ecological changes unfolding over years to decades at landscape and regional scales, and these models are being scaled to the global level (Levin et al., 2013; Liu et al., 2013; Verburg et al., 2015). Nevertheless, to model human–environment interactions in geologic time at global scales – as a 'global human climate system', it is necessary to simulate the emergence of behaviorally modern human societies as small bands of hunter-gathers in Africa more than 50,000 years ago, their spread across the globe and their diversification into myriad societal forms, from horticultural to agrarian, pastoral, and industrial. From this perspective, existing modeling efforts are more limited in scope, analogous to the simulation of a 'human weather' in which the underlying structuring conditions shaping human societies and their environment interactions are held relatively constant over time.

To understand the emergence, diversification, and dynamics of a global 'human climate system' across diverse human societies and the landscapes they have shaped from Pleistocene to present, theoretical frameworks and modeling approaches must incorporate mechanisms that facilitate major long-term structural changes in the organization of societies and their capacity to transform landscapes (Ellis, 2015). Anthroecology theory provides such a framework through sociocultural niche construction (SNC), an evolutionary theory coupling human social change and ecosystem engineering (Ellis, 2015; key terms in anthroecology theory are defined in Appendix 1). Anthroecology theory is supported by empirical relationships between social and landscape patterns and dynamics. However, the evolutionary mechanisms underpinning these relationships cannot be confirmed through empirical evidence alone.

This paper examines the potential to explore and test the long-term evolutionary mechanisms of anthroecology theory through an agent-based virtual laboratory (ABVL) approach. Developing an operational ABVL capable of simulating evolutionary processes across human societies and landscapes over the past 50,000 years is an ambitious project well beyond the reach of this paper. The focus here is preliminary: to examine the prospects for developing an ABVL capable of testing the predictions of anthroecology theory through generative social simulation. This will be accomplished by developing a general modeling framework specification, set of guiding questions, and illustrative examples linking sociocultural and landscape change. Even as a thought experiment, the effort to join anthroecology theory with an ABVL approach will be shown to advance LSS theory toward a broader framework for understanding the processes that have enabled behaviorally modern human societies to diversify, scale up, and reshape Earth's landscapes in profoundly different ways over the past 50,000 years.

## 1.1. *Theoretical foundations*

### 1.1.1. *Anthroecology and sociocultural niche construction (SNC) theory*

Anthroecology and SNC theory are based on the principle that behaviorally modern human societies coevolve with the ecosystems and landscapes that they shape and that sustain them through long-term processes of natural, cultural, and artificial selection acting on the cultural, ecological, and material inheritances of human individuals, social groups, and societies (Ellis, 2015; Figure 1; terms in Appendix 1). This broadly 'inclusive' view of evolutionary processes is based on the Extended Evolutionary Synthesis (Danchin, 2013; Danchin et al., 2011; Fuentes, 2016; Laland et al., 2015), in which cultural inheritances – socially learned behaviors ranging from exchange relations to the 'recipe' for making a tool (Hill, Barton, & Hurtado, 2009; Mesoudi, Whiten, & Laland, 2006; Richerson & Boyd, 2005) are coupled with ecological inheritances – the inherited adaptive consequences of engineered environments – the basis for niche construction theory (Odling-Smee, Laland, & Feldman, 2003). Cultural inheritances underpin the adaptive fitness of behaviorally

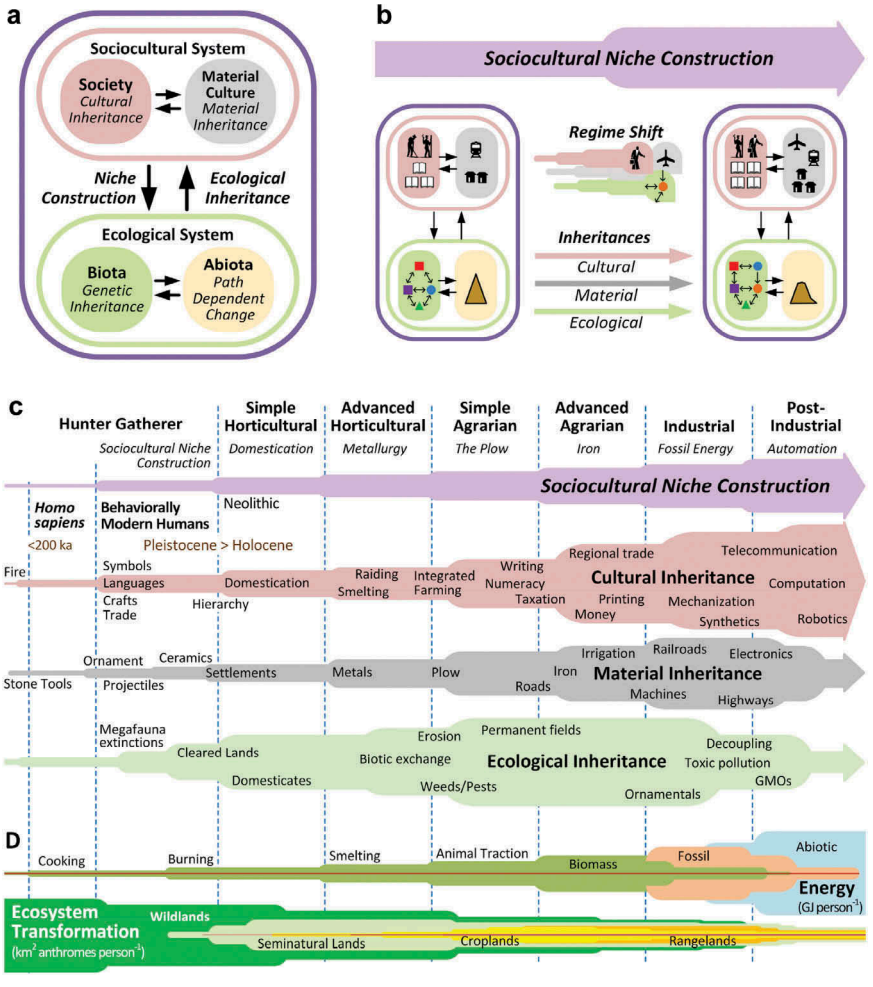


**Figure 1.** Conceptual models of anthroecosystems, sociocultural niche construction (SNC), and differences in SNC across major types of sociocultural systems. (a) An anthroecosystem combining sociocultural and ecological systems through heritable and path-dependent interactions. (b) Long-term change in anthroecosystems caused by gradual and regime shifts in cultural, material, and ecological inheritances. Regime shift illustrated by new trading system (cultural + material inheritance) + facilitated species invasion (orange dot) + new biotic interactions (arrows). Path-dependent abiotic change is depicted as erosive reshaping of brown landform. (c) Long-term regime shifts in SNC and their relative accumulation of cultural, ecological, material inheritances (relative heights of pink, gray, and green bars). (d) Relative per capita energy expenditure and per capita transformation of landscapes in terms of relative anthrome area used across different types of sociocultural systems. Widening purple bar depicts increasing role of SNC in shaping anthroecosystem structure and function. All Y axes indicate relative, not absolute, changes. Based on Figures 2 and 3 in Ellis (2015).

modern humans, the organization and the functioning of societies, and their socially-enacted strategies for subsistence exchange (i.e. sharing, trade) and engineering environments – their subsistence regimes (Boyd, Richerson, & Henrich, 2011; Henrich, 2015; Hill et al., 2009; Mesoudi, 2011; Mesoudi et al., 2006; Richerson & Boyd, 2005; Richerson et al., 2016; Sterelny, 2011). SNC theory also incorporates 'material inheritances' – the heritable material culture of human societies capable of altering adaptive fitness, from ceramics to roads to plastic pollution (Ellis, 2015; Appendix 1).

SNC theory couples evolutionary changes in sociocultural systems (societies, groups) with ecological systems in 'anthroecosystems' through selection processes acting on cultural, ecological, and material inheritances (Figure 1(a)). While appearing structurally similar to existing SES and

CHANS models of human–environment interactions, anthroecosystem models focus not on direct interactions between societies and ecosystems, but on the long-term evolutionary processes that shape the structure of these interactions over centuries to millennia – that is, on the dynamics of 'human climate' rather than 'human weather'. As natural, cultural, and artificial selection act on the cultural, ecological, and material inheritances of individuals, groups, and societies, anthroecosystems undergo long-term structural changes. Such changes occur both gradually through the accumulation of novelty, loss, and random drift of inheritances, and through more dramatic regime shifts in producing transformative changes in anthroecosystem functioning, analogous to the process of punctuated equilibrium in biological evolution (Figure 1(b)).

The human sociocultural niche has evolved increasing dependence on cultural, material, and ecological inheritances over the long term, producing larger and more complex societies and the accumulation of cultural inheritances from the plow to taxation, material inheritances from ceramics to roads, and ecological inheritances from domesticates to agricultural fields to weeds and toxic pollutants (Figure 1(c)). In the 50,000 years since behaviorally modern humans first spread out of Africa, the potential scale of human societies has grown from a few dozen to a few hundred million individuals; the potential productivity of a single square kilometer of land has been intensified from sustaining less than 10 to more than 1000 individuals; energy use per individual has expanded by more than 20 times; and societal flows of materials, energy, biota, and information are now essentially global (Figure 1(c,d); Ellis, 2015). While there is huge variation among human societies, including diverse hybrid forms, and long-term trends are nonlinear, there is clearly a long-term trend toward larger societal scales over time, increasingly intensive transformation and use of land, and for increasing energy substitution and energy use as societies scale up (Figure 1 (c,d)).

### 1.1.2. *Evolving sociocultural landscapes*

As societies and their processes of SNC evolve, anthroecosystems change and these changes are expressed differentially across landscapes. Anthroecology theory holds that the SNC processes of a given society acting on a given landscape can be described across *time* and *space* as a state function combining two sociocultural structuring factors, *society* and social *centrality* together with a third hybrid social-ecological structuring factor, land *suitability*, as:

$$\textit{Sociocultural niche construction} = f(\textit{society}, \textit{centrality}, \textit{suitability}, \textit{time}, \textit{space}) \tag{1}$$

The *society* factor defines the subsistence regimes, social organization, and other heritable cultural traits governing the SNC capacities and tendencies of a given society – exemplified by the major differences among societies in Figure 1(c). Social *centrality* combines central place theory (Christaller, 1933; Verburg, Ellis, & Letourneau, 2011; von Thünen & Schumacher-Zarchlin, 1875) with theory on social network centrality, of which there are multiple measures (Brughmans, 2013; Rivers, Knappett, & Evans, 2013; Zhong, Arisona, Huang, Batty, & Schmitt, 2014). *Centrality* defines the degree to which a given space serves as a functional center of human social interactions, such as power and exchange relationships, on a scale from low (remote areas, periphery, low-ranking actors) to high (sacred sites, cities, market centers, powerful elites) within a given society or across societies interacting within a world system. In urbanized societies, intense social interactions in areas of high social centrality – primarily urban centers – produce economies of scale and social benefits unavailable in less central places (Bettencourt, 2013). The spatial patterning of social centrality produces socially and culturally-dependent patterns of spatial heterogeneity, such as dense urban cores, market influenced development along road networks, and low-intensity land use in remote areas.

Spatial patterns of SNC are also expressed differentially within and across landscapes depending on land *suitability*, the potential productivity of land in sustaining the subsistence regimes of a given *society*. Land *suitability* varies spatially in relation to terrain (slope), soil quality, and water

accessibility and also depends on a given societies' subsistence regimes within a specific biome and its patterns of social centrality. For example, desert biomes may have different suitability patterns than rainforests and this may also depend on whether a given society is agricultural or industrial; societies dependent on rice cultivation find wetlands highly suitable for agriculture while societies dependent on upland crops like wheat and maize may consider wetlands unsuitable – unless they have the capacity to drain them. Nevertheless, there is a general tendency across societies for the highest suitability to occur in areas with level terrain and accessible surface water and these areas tend to be sites of early and persistent human use and settlement (Ellis, 2015).

If we combine the three structuring factors of SNC with biomes, we obtain a general state expression defining the long-term formation and dynamics of anthroecosystems and their shaping of anthropogenic landscapes as:

$$Anthroecosystems = f(biome, society, centrality, suitability, time, space) \quad (2)$$

Based on this state function, anthroecology theory holds that the social and ecological patterns and processes within and across biomes and landscapes can be predicted from the SNC capacities of a given society and their differential expression in relation to spatial patterns of social *centrality* and land *suitability*. In other words, the spatial patterns and dynamics of a given landscape within a given biome inhabited by a given society can be predicted from its patterns of land suitability and social centrality. Further, just as variations in ecological patterns and processes can be conceptualized as 'sequences', as in chronosequences (time), toposequences (terrain), and climosequences (climate), anthroecology theory uses 'anthrosequences' to depict variations in ecological patterns and processes caused by variations in SNC acting on a given biome over the long term.

In Figure 2, an anthrosequence based on a stylized temperate woodland biome landscape illustrates predicted variations in anthroecological patterns and processes in four different types of societies in relation to spatial variations in social centrality and land suitability. Though the patterns from left to right in Figure 2 might be interpreted as changes over time, and settlement and environmental patterns are drawn to allow this, societal transitions may certainly occur in different orders, for example, hunter gatherer to industrial. Moreover, anthrosequences differ profoundly in different biomes, with similar societies producing very different landscapes in grasslands versus deserts, for example.

As illustrated at right in Figure 2(a), industrial and agrarian societies show highly differentiated patterns of land use in relation to social centrality, with urban areas and interconnecting infrastructures (roads, canals, etc.) with higher centrality clearly distinguished from remote and less connected rural areas, and their sociocultural transformation of landscapes differs accordingly, both in intensity and types of ecosystem engineering. Even in mobile hunter gatherer societies (at left in Figure 2(a)), which generally have low levels of social inequality and therefore limited variance in social centrality, spatial differentials in centrality and SNC relating to distribution of populations, power, and exchange relations can generally be observed in relation to scarce resources such as surface water, tool-making materials, and fertile hunting grounds and foraging areas (Smith, 2011b); these may also be understood as higher and lower degrees of social centrality, with more central and concentrated populations enjoying economies of scale (Hamilton, Milne, Walker, & Brown, 2007).

The anthrosequence in Figure 2 presents basic predictions of anthroecology theory in relation to the spatial patterning of landscapes by SNC processes, in terms of human populations, land use, and land cover (Figure 2(a,c)), the distribution of anthromes across regions (Figure 2(b)), and the long-term ecological consequences of these structuring processes in terms of megafauna populations, net primary production, fuel combustion, and soil fertility across landscapes (Figure 2(c)). Given these landscape predictions of anthroecology theory, which are generally confirmed by empirical patterns across the anthropogenic biosphere, the challenge now is to develop the rigorous theoretical models and experiments that might enable testing the evolutionary mechanisms of SNC theory as the basis for these predictions.

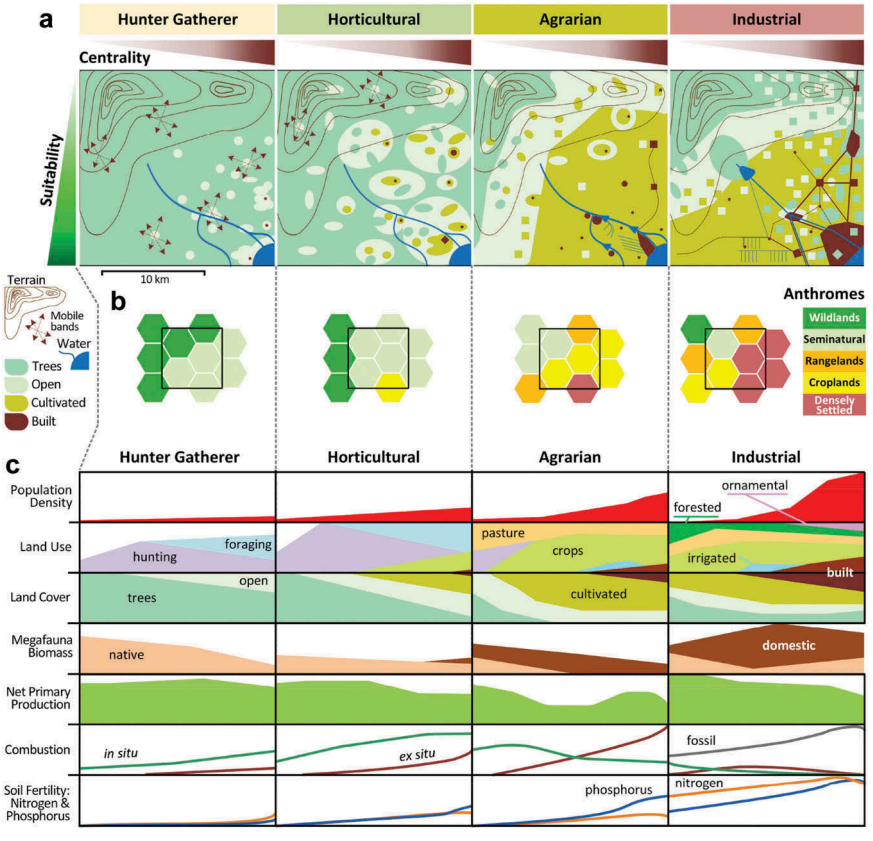


**Figure 2.** Anthrosequence in a stylized temperate woodland biome illustrating conceptual relationships among society types and social centrality and their interactions with land suitability for agriculture and settlements in shaping the spatial patterning of human populations, land use and land cover, and their ecological consequences. Settlement patterns are drawn to allow interpretation as a chronosequence of societies from left to right, however, alternate transitions are also likely, for example, from hunter gatherer to industrial. (a) Anthropogenic transformation of landscapes under different sociocultural systems (top) relative to spatial variations in social centrality (horizontal axis; same for all charts below) and land suitability (vertical axis). Landscape legend is at far left. (b) Anthrome level patterns across regional landscapes (black box frames landscape in (a)). (c) Variations in human population densities and relative land-use and land cover areas (white = no human use of any kind; ornamental land use = parks, yards), relative megafauna populations in terms of biomass (not including humans; native and domesticated), and relative variations in ecosystem processes, including net primary production, combustion of biomass *in situ* (natural fires, unintended anthropogenic fires, and intended fires, e.g. land clearing), *ex situ* (hearth fires, cooking, heating), and fossil fuels, and soil fertility in terms of reactive nitrogen and available soil phosphorus. Based on Figure 5 in Ellis (2015).

### 1.1.3. *Agent-based models as virtual labs for sociocultural landscape evolution*

Perhaps the most fundamental challenge in developing a mechanistic understanding and testing of anthroecology theory is that processes of SNC are neither socially nor environmentally deterministic, but rather emerge through individual human and social group decisions and actions within anthroecosystems produced by culturally inherited social, material, and ecological structures (as in 'structuration theory'; Giddens, 2013). While individuals may act largely on the basis of culturally inherited traits, they may also choose among and adopt cultural traits in different ways, yielding substantial variance and unpredictability in individual, group, and societal behavior (Henrich, 2015; Macy & Willer, 2002; Waring, Kline, et al., 2015).

To understand the social and landscape patterns and dynamics produced by SNC, processes of individual decision-making must therefore be integrated with evolutionary processes shaping the culturally, materially, and ecologically inherited conditions upon which anthroecology theory is based, as illustrated in Figure 3. Further, these processes and their consequences in terms of

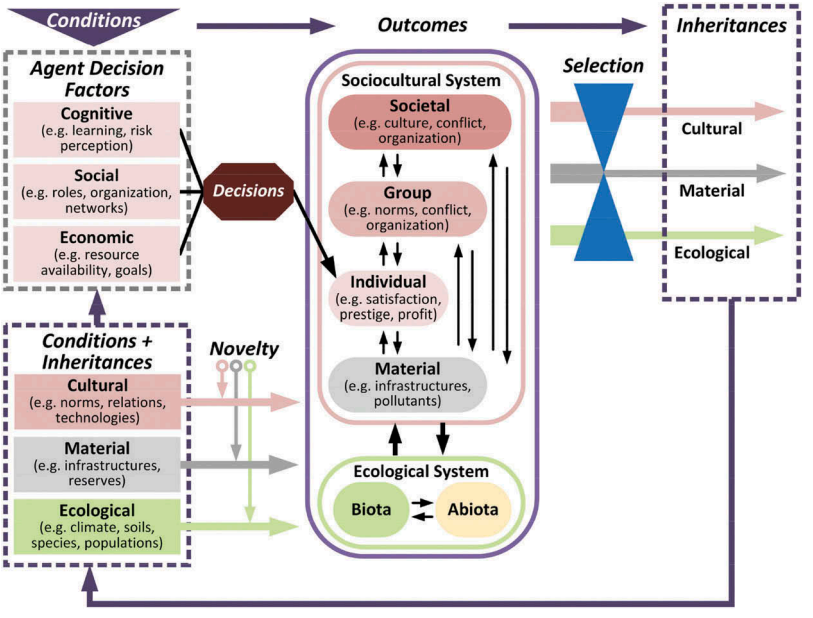


**Figure 3.** Generalized agent decision-making framework linking *Agent Decision Factors* with anthroecological *Conditions* and *Inheritances* in generating agent *Decisions* with differential emergent *Outcomes* for individuals, groups, and societies and the material and ecological patterns and processes of anthroecosystems (Figure 1(a)). Differential *Outcomes* result in *Selection* for beneficial cultural, material, and ecological *Inheritances* and against those producing detrimental outcomes. Selected *Inheritances* are transmitted as feedbacks influencing future *Conditions*. *Novelty* in cultural, material, and ecological inheritances (e.g. cultural innovations and borrowings, material culture acquired through trade or warfare, species introductions and invasions, and territorial expansion) also contributes to *Outcomes*, as a process of novel characteristic generation analogous to genetic mutations. Figure adapted from Jain, Naeem, Orlove, Modi, and DeFries (2015) and Waring, Kline, et al. (2015).

landscape patterns and dynamics must be distinguishable as an evolutionary mechanism, with natural, cultural, and artificial selection acting on cultural, material, and ecological inheritances, from alternative models in which human behaviors are either defined by biological traits and demographics alone (sociobiology; Wilson, 1975) or by unchanging, 'economically-rational', 'Homo economicus' decision-making processes (Henrich et al., 2005). Differentiating among such models through conventional experimental methods is made nearly impossible by the scale and complexity of anthroecosystems, LSs, CHANS, and SESs (Levin & Clark, 2010; Magliocca, 2015). Thus, simulation models have become an important tool among a portfolio of methods for researchers attempting to understand the structure and dynamics of SESs and to build general causal theory on human–environment interactions (Brown, Verburg, Pontius, & Lange, 2013; National Research Council [NRC], 2014).

Agent-based models (ABMs), in particular, have been applied to a diverse range of SES, since human actors have been recognized as primary agents of change shaping the structure and function of ecosystems and landscapes (Ellis & Ramankutty, 2008; Rounsevell et al., 2014) and ABMs have the ability to explicitly represent human decision-making processes (An, 2012; NRC, 2014). Many early ABMs were developed in the spirit of 'generative social science' (Brown, Aspinall, & Bennett, 2006; Epstein, 1999), which aimed to engage with and test theory by reproducing complex, emergent social system-level phenomenon from a few simple, bottom-up rules (Janssen & Ostrom, 2006; O'Sullivan et al., 2016). These early models were the first implementations of theory in a simulation environment that could account for the role of agent heterogeneity in emergent phenomena such as segregation (Schelling, 1971), tit-for-tat strategies in the prisoner's dilemma (Axelrod, 1986), and civil violence (Epstein, 2002). As the methodology gained traction, more emphasis was placed on empirically grounding ABMs, and

a shift occurred toward more realistic models applied to a particular case study (Janssen & Ostrom, 2006). While the proliferation of case-based ABMs is a sign of a maturing research method, progress toward the development of general theories of human–environment interactions with current approaches is not evident (NRC, 2014). This has recently led some to ask: can ABMs contribute to the ultimate goal of building coherent theory about the structure, dynamics, and sustainability of SESs (O'Sullivan et al., 2016)?

Here we describe a virtual laboratory approach for moving LSS toward the 'generative social science' mode of inquiry in an effort to develop and test a general theory on human–environment interactions. We describe the use of a generalized ABM framework to model emergent anthroecological patterns and processes produced by human individuals, groups, and societies interacting with each other in transforming ecology across landscapes and regions, and responding to and learning from these changes across human generational time (Hedström & Ylikoski, 2010; Macy & Willer, 2002; Magliocca & Ellis, 2013; Magliocca, Brown, & Ellis, 2013, 2014; Turchin, Currie, Turner, & Gavrilets, 2013). The ABM description and specification follows a partial Overview, Design Concepts, and Details (ODD) protocol that includes human decision-making (ODD+D; Grimm et al., 2010; Müller et al., 2013).

## 2. The virtual lab approach to understanding long-term landscape change

### 2.1. *Purpose*

The overall purpose of the ABVL approach is to explain the emergence, dynamics, and spatial patterning of anthropogenic landscapes (anthroecological change) from first principles of agent objective-seeking behavior in response to changing cultural, material, and ecological conditions according to SNC theory. This preliminary ABVL specification represents a generalized model framework that enables systematic generation and testing of hypotheses of the extent to which culturally inherited human sociocultural processes were/are important for reshaping natural landscapes and producing the patterns and dynamics of anthropogenic landscapes, such as the anthrosequences in Figure 2. The application of this framework entails virtual experiments that correspond in methodology with real experiments. Virtual experiments are designed in such a way that a suite of generalized sociocultural evolutionary mechanisms at agent and group levels that are hypothesized to be important are systematically introduced and compared against empirical observations and null model outcomes. Upon observing the results of the initial model specification, an iterative modeling process ensues in which alternative hypotheses are devised, the model specification altered in a controlled and reproducible way, and simulations are conducted to test the new model specification and hypotheses (i.e. 'strong inference; Platt, 1964). The ultimate goal of such an approach is not to predict land-use changes or landscape evolution in any particular location. Rather, the ABVL approach is useful for formalizing assumptions and testing the logic of proposed mechanisms of SNC by producing both qualitative and quantitative hypotheses comparable against data (Turchin et al., 2013) and identifying relative differences in socioculturally driven landscape transformation processes under different social and environmental conditions.

To operationalize the ABVL approach, the specification of system processes and agent attributes must necessarily be generalized and grounded in theory to be broadly applicable, but also sufficiently empirically grounded to conduct model evaluation against real data and evaluate whether additional explanatory power is gained through introducing new mechanisms. A major challenge for developing the ABVL approach, then, is to find the proper balance between the number and types of interactions represented and the generality of their representation (Magliocca et al., 2014).

### 2.2. *Entities, state variables, and scale*

Entities in the ABVL consist of agents (Table 1), resources and spatially explicit patches of land (Table 2). Although social groups exist, decisions are not made at the group level, rather agent

**Table 1.** Description of the agent attributes.

| Attribute | Description | Source |
|---|---|---|
| Age | Time steps that household is in simulation | NA |
| Mortality probability | Probability of agent removal after 20 time steps, increases slowly (e.g. 1%) each successive time step | NA |
| Location | Patch(es) of land occupied by agent | NA |
| Ownership | Patch(es) of land owned by agent. Can be different than land occupied | NA |
| Household size | An agent represents an abstracted household consisting of two adults and two children, and children provide and require half as much labor and food, respectively, as adults | Evans et al. (2001) |
| Income stock | Cumulative monetary and/or in-kind income resulting from land-use practices and/or non-land-based livelihood activities less expenditures. Can be vertically inherited from 'parent' agents, and may include material inheritances, such as buildings, tools, or precious metals | NA |
| Food stock | Food resources from annual production and/or purchases net of storage losses | NA |
| Land-use practices | Socially-learned subsistence strategies for land use (foraging, controlled fire, propagation, cultivation, grazing) and their intensity (rates of harvest/cultivation/stocking and use of external inputs). May vary spatially with land suitability and land tenure relations | Magliocca et al. (2013, 2014) |
| Non-land-based livelihood activities | Income-generating activities that are not natural resource based. Production of handicrafts in agrarian societies, wage labor in commercial settings | Magliocca et al. (2013, 2014) |
| Labor supply | Total available labor, expressed in person-weeks. Calculated by multiplying a year's worth of labor net of required 'home' time (e.g. leisure, home maintenance, home textiles, etc.) by the agent's household size | Evans et al. (2001); Macmillan and Huang (2008) |
| Subsistence demand | Minimum subsistence (calories and protein required for household and livestock consumption) and income requirements (equal annual external input costs plus the cost of a year's worth of food should land-use production fail) multiplied by the household size | Magliocca et al. (2013, 2014); Penning De Vries, Rabbinge, and Groot (1997) |
| Livelihood risk preference | Preference for engaging in subsistence- (low risk) versus exchange-oriented (high-risk) livelihood activities. Expressed as 0 (risk adverse) to 1 (risk seeking) weighting drawn from random distribution | Magliocca et al. (2013, 2014); Netting (1993) |
| Predictive success | Cumulative prediction error of agent payoff expectations (see *Predictions* below) | Arthur (1994); Arthur, Durlauf, and Lane (1997) |
| Group identifiers | Social group affiliation is inherited but modifiable by cooperation trait and/or level of income stock | Waring, Goff, et al. (2015) |
| Cooperation traits | Traits governing agent's likelihood of exchanging food and/or income within social group: share with no one, conditional cooperators, or always cooperate. Inherited from parent agent but modifiable through learning from agent interactions (see *cooperation* submodel) | Ostrom (2000); Waring, Kline, et al. (2015) |
| Reputation | Cumulative history of agent cooperation or defection in resource exchange | Van Vugt, Roberts, and Hardy (2007) |
| Conformity traits | Inherited traits governing agent's response to *social norm formation* building-block process and norm of affiliated social group: innovator (ignore social norm), adopter (conformity only after threshold of member group conforms and/or threat of punishment for not conforming), conformer (instant group conformity) | Berger (2001); Mesoudi et al. (2006) |
| Aspiration traits | Inherited traits but subject to group affiliation. Subjective standards of material well-being specified by *aspiration formation* building-block process and dependent on livelihood risk preference, social norms, and group affiliation. Minimum aspiration levels are equal to subsistence needs | Scoones (2009) |
| Social connectedness | Agent's position and number of links in social network specified by *social network influences* building-block process | Manson et al. (2016) |

**Table 2.** Description of resource and land patch attributes.

| Resource attribute | Description | Source |
|---|---|---|
| Ecological inheritances | Accessible stocks of usable plant and animal wild foods and other biotic resources, cultivars, and/or livestock units adapted to local biophysical conditions. Inherited from natural ecosystem (biome) and within and across social groups and other societies (by exchange). May vary spatially with land suitability | Klein Goldewijk and Ramankutty (2004); Monfreda, Ramankutty, and Foley (2008) |
| Material inheritances | Accessible stocks of usable abiotic and artificial resources including precious minerals, tools and other artifacts, and engineered landscape infrastructure such as buildings, roads, and irrigation systems. May vary spatially, and may modify resource access and quality | Experimental condition; Magliocca (2015); Magliocca et al. (2013, 2014); Smith (2011a) |
| **Land patch attribute** | **Description** | **Source** |
| Land use | Functional land use characterized by yield of best available subsistence regime in relation to society and agent (e.g. useful wild or domesticated plants and animals, agricultural technology, and intensity of land management) | Experimental condition; Magliocca (2015); Magliocca et al. (2013, 2014) |
| Soil type constraint | Reduction in potential yield due to soil type. May vary spatially | For example, Global Agro-Ecological Zones (GAEZ, 2011a) |
| Slope constraint | Reduction in potential yield due to limitations on soil quality and utilizable subsistence strategy due to slope (e.g. tillage). May vary spatially | For example, GAEZ (2011a) |
| Climate constraint | Reduction in potential yield due to precipitation and growing days (includes temperature and pest factors) limitations. May vary spatially | For example, Global Agro-Ecological Zones (GAEZ, 2011b) |
| Harvestable yields | Average annual yields of wild foods, cultivars, livestock for most productive subsistence regime available to agents, reported in kcal/ha equivalents. Varies spatially dependent on suitability constraints and land-use practices | Monfreda et al. (2008); Klein Goldewijk and Ramankutty (2004) |
| Degradation rate | Rate of annual yield decline after repeated flora and fauna harvest, cultivation, and/or grazing without external fertility inputs (i.e. 'extensive' agriculture). Degradation is zero and/or reversed by external fertilizer inputs and other intensive land-use practices | Siebert and Döll (2010); Tiessen et al. (1992) |
| Regeneration rate | Rate of potential yield rebound during periods of fallow, varies with constraints and prior land-use practice, including burning, tillage intensity, cultivar type | Tian, Kang, Kolawole, Idinoba, and Salako (2005); Tiessen et al. (1992); Tyson, Roberts, Clement, and Garwood (1990) |
| Access to markets | Represented as travel time (as additional labor costs) to places of exchange, which are modified by infrastructure that can be materially inherited from previous generations and/or introduced through coordinated group or societal efforts | Derived following Verburg et al. (2011) |
| Access to water | Represented as higher or lower labor or capital investments required to obtain water sufficient for drinking and/or to produce a potential agricultural yield | Experimental condition; Magliocca (2015); Magliocca et al. (2013, 2014) |

decision-making may be contingent on group affiliation, and as a single agent might belong to multiple groups, making decisions according to social group context.

#### 2.2.1. *Agents*

Agents are autonomous decision-making entities with the potential to accumulate cultural, material, and ecological inheritances, reproduce or not, and form social groups based on group affiliation. An agent is defined as a reproductive and immediate kin unit. In reality, the actual form of this unit can differ substantially in their individual makeup among hunter-gatherer, agrarian, pastoral, and industrial societies (Dyble et al., 2015; Ellis, 1993; Netting, 1993). But for generality, we conceptualize an agent as consisting of two adults and two children, and children provide and require half as much labor and food, respectively, as adults (Evans, Manire, de Castro, Brondizio, & McCracken, 2001). This conceptualization is consistent with empirical work that found regular hierarchical structuring of human group sizes, regardless of society type, of which 3–5 individuals was found to be the mean smallest stable size (i.e. the 'support' clique; Zhou, Sornette, Hill, & Dunbar, 2005). Functionally, this aligns with 'households' in agrarian and industrial societies (Ellis, 1993; Netting, 1993). For hunter-gatherer societies, this represents an organizational unit in which kinship, reproductive, and resource allocation interactions are sufficiently homogeneous to be treated as a single decision-making unit for modifying the landscape. Thus, agents will be referred to as households, regardless of society type, from this point forward for generality. Although agents can form social groups, social groups in themselves do not have agency. Rather, social groups influence the decisions of agents through social norms. Thus, the collective 'behavior' of a social group is determined by adherence (or not) of its constituent agents to group norms, as opposed to the social group having any independent decision-making ability.

#### 2.2.2. *Environment*

Environment is represented as the combination of ecological and material inheritances that condition the availability of resources on which livelihoods depend. Two types of environmental entities are represented: *resources* (which may or not vary spatially) and *land patches* (connected with agents as usable territory or land tenure rights). Descriptions of each of these are provided in Table 2. *Land patch* attributes vary across the landscape and directly influence the land management decisions of the occupying agent or agents. To maintain generality and applicability across a diversity of environmental settings, land uses are defined by functional group, rather than crop-management combinations (e.g. foraging, shifting cultivation, upland vs. irrigated paddy rice), and vary in their potential productivity, degradation/regeneration rates, and labor costs. Land suitability for use is determined by the combination of slope, soil, and climate constraints, which limit the ultimate potential yield of any harvested output or crop or livestock production system. Yields are endogenously determined subject to environmental constraints on agricultural productivity (including stochasticity) and agents' land-use actions. *Resources* consist of the productive resources (e.g. wild food sources, cultivars, or livestock) known to agents in a society (ecological inheritance) and any heritable material alterations (e.g. pollution), engineered landscape structures (e.g. settlements and roads), or technologies (e.g. tools) that modify resource access and/or quality (i.e. material inheritance).

Biophysical processes of primary production, secondary production (e.g. game, livestock), land degradation, regeneration, and succession are represented using a simplified set of rules (see Magliocca et al., 2013 for an example applied to agrarian societies). These assumptions allow the generalization of land uses by management intensity, while still allowing for the possibility that management practices lead to inefficient yields even with the best cultivars. Access to water can be represented as higher or lower labor or capital investments required to obtain water sufficient to produce a potential agricultural yield (Magliocca et al., 2014). Access to markets, or more generally opportunities for exchange, are modified by infrastructure, which can be materially inherited from

previous generations and/or introduced through coordinated group efforts as landesque capital (Håkansson & Widgren, 2014; Sen, 1959).

#### 2.2.3. *Spatial and temporal scales*

Landscapes are represented with cellular grids (e.g. Magliocca et al., 2014 used 1 ha cells). The extent of the simulated landscape can vary depending on the scale of the human society or societies in a specific experimental design, from those of hunter-gather territories to agricultural villages, or large regions. All agent attributes, learning, and environmental conditions are updated at annual time steps.

### 2.3. *Process overview and scheduling*

The following provides a simplified version of the process overview and scheduling. For more detail regarding each process or agent attribute involved (*italics*), please see the *Submodels* section below. At initialization, agents and environmental conditions are set up. The following sequence of simulated processes repeat every time step.

- **Environment**: Update ecological state of land patches based on time in use of the current land use subject to degradation/regeneration rates.
- **Learning and prediction**: Formation of payoff expectations (e.g. price, yield, social value) for all land use and livelihood activities based on agent's past experience and/or observations from their social network.
- **Social norms**: Update available subsistence strategy options, including cooperation strategies (see *social norm formation*).
- **Labor allocation**: Based on current levels of food and income stocks relative to aspirations (subject to *aspiration traits*), labor is allocated among land- and non-land-based livelihood activities subject to income expectations, risk perceptions, and/or social group influences (subject to *conformity traits*). If applicable, labor is allocated to the construction of productive infrastructures (e.g. irrigation systems).
- **Production**: Food and income payoffs are realized from land uses and non-land-based livelihood activities.
- **Resource sharing**: Depending on agent's *cooperation* and *conformity traits*, contribute/exchange portions of resources to other group members, update agent's reputation (see *social norms formation* and *cooperation*).
- **Competition**: If subsistence needs *or* aspirations are not met, agents expand land holdings (see *land allocation* and *competition*).
- **Reproduction**: If resources and agent age are sufficient, agent reproduces (see *Reproduction*) and passes along heritable traits, including cultural traits for norms and subsistence strategies (land-use practices and non-land-based livelihood activities).

### 2.4. *Design concepts*

#### 2.4.1. *Theoretical background for agent decision model*

This ABVL framework synthesizes multiple theoretical frameworks to inform the scoping, conceptualization, and implementation of the ABM. The overarching theoretical framework is SNC, which builds upon foundations of induced intensification theory (e.g. Boserup, 1965; Turner & Ali, 1996), smallholder livelihood strategies, (de Janvry, Fafchamps, & Sadoulet, 1991; Ellis, 1993; Netting, 1993; Scoones, 2009), and cultural evolution (e.g. Henrich, 2015; Mesoudi et al., 2006; Waring, Kline, et al., 2015). In particular, the concept of livelihood strategies provides mechanistic depth to 'subsistence regimes' as a general framework for modeling land-use decisions

and their individual, group, and societal outcomes in response to changing social and/or environmental selection pressures. According to Ellis (1993), a livelihood strategy is a set of activities for generating income, both cash and in kind, subject to social institutions (e.g. group, village, society) and access rights upon which livelihood activities depend to support and sustain a given standard of living. Livelihood strategies can consist of a mix of natural resource-based production activities, or simply land use, and non-production activities (e.g. employment for income or in-kind wages). Even if natural resource exploitation is of prime interest, one must consider land use and non-production activities jointly because of the inseparability of individual or household time (i.e. labor) and resources (de Janvry et al., 1991). Non-production activities influence and are influenced by the amount of labor allocated to and economic returns of land use. Livelihoods also depend on natural resources and their dynamics over time (e.g. De Sherbinin et al., 2008; Folke, Colding, & Berkes, 2003) linking the adaptive fitness returns of subsistence regimes with ecological processes, as ecological inheritances. Therefore, a general model of anthroecological landscape change necessarily considers land-use and non-production decisions of agents to be socially, culturally, economically, and ecologically coupled with the dynamics of ecosystem structure and function across landscapes and regions.

### 2.4.2. *Agent objectives*

Each agent is initiated with an objective function with particular aspirations (e.g. mix of subsistence-focused vs. profit-maximizing vs. prestige building) and risk tolerance levels (e.g. for perceived risk of adopting new technologies), which are heterogeneous 'traits' across the agent population. These traits are randomly assigned for the first agent generation, and inheritable and subject to random variation across agent generations (i.e. genetic drift). Agents balance two related livelihood objectives: (1) minimize risk and labor in land use to meet subsistence food requirements; and (2) minimize risk in and maximize return from income-generating and social activities to meet or exceed income and social aspirations and meet food requirements through exchange. Each agent allocates labor to a mix of production and non-production activities to meet those objectives, and the specific mix depends on the set of livelihood options available to them and their individual attributes. Access to land-use and non-land-based livelihood options, or livelihood choice set, is determined by each agents' endowments of natural capital (e.g. land suitability) and non-natural capital (e.g. cultural and material inheritances, economic resources, social status) (Ellis, 1993; Netting, 1993). Each agent attempts to meet their livelihood and social objectives by optimizing across their livelihood choice set subject to individual aspirations and perceptions of risk in income-generating activities, social norms, and expectations for future environmental conditions and income from production and non-production sources. Based on available labor allocated to production activities, an agent decides the optimum land use and intensity of management for each land unit an agent manages based on expected payoff (agricultural yield and profit subject to risk perceptions), physical input requirements, and labor costs. This optimization process is adaptive because agents learn the real payoffs from each option in their choice set over time, and can shift between different land use options and/or to non-production livelihood activities if selective pressures emerge, such as declining productivity or socially transmitted alternative strategies.

### 2.4.3. *Learning and prediction*

Agents have a set of prediction models for forming expectations of future returns on harvestable yields (both wild and domesticated) and/or crop and livestock prices that they update each period as new information becomes available. Agents form expectations by detecting trends in past observations and extrapolating those trends one period into the future. The performance (i.e. error) of each model is tracked every period, and the agent acts on the prediction of the currently most successful model (i.e. the 'active' model). In the next period, actual yields and prices are

realized and model performances are updated. An example implementation of this 'backward-looking' expectation formation algorithm can be found in the supplemental material for Magliocca et al. (2013) available online. Agents are therefore able to learn which models best predict yield and price trends, and can adaptively switch to following the predictions of a previously 'dormant' model if it outperforms the current 'active' model when conditions change. Agents also evaluate the success of inherited behaviors (e.g. cooperation trait) via reinforcement learning (e.g. Roth & Erev, 1995). For example, agents with the 'conditional cooperator' trait (see Table 1 and *cooperation* submodel) can adaptively reduce the amount of resources exchanged with group members if past exchanges were not reciprocated.

## 2.5. *Implementation details*

### 2.5.1. *Building-block approach*

In order to operationalize sociocultural evolution and multilevel cultural selection in our ABVL approach, we introduce the concept of building-block processes (Cottineau, Chapron, & Reuillon, 2015; Magliocca, 2015; O'Sullivan & Perry, 2013). Each trait can be represented as a 'building-block' of a society type, with different variations of a given trait represented as 'levels' (Table 3). The ways in which various levels of multiple traits interact to produce a coherent culture are 'building-block processes'. The goal of this model architecture is to find the most parsimonious configuration of building-block processes needed to explain observed anthroecological patterns as the emergent result of agent-agent and agent-environment interactions, different mixes of individual and group traits, and variations in social and environmental selection pressures.

Building-block process Levels are organized hierarchically such that each successive Level builds on the previous. Further, moving from Level 1 to 4 is associated with linearly increasing model *complicatedness*, but a nonlinear relationship with *complexity* of the system being modeled. This distinction implies meaning different than the everyday usage of these terms (Sun et al., in press), and reflects differences in the effects of building-block process Levels on model structure versus model behavior. Model complicatedness is defined as the number of state dependencies that affect agent behavior and interactions, and is measured by the number of parameter inputs needed to operationalize a given building-block process Level. For example, agent-level profit-maximization requires fewer agent and environment state variables than a satisficing model, which additionally requires an agent's risk preferences and/or the state of other agents if subjective aspirations are involved. At the group level, agent-to-agent cooperation requires additional agent traits and knowledge of other agents' actions, both of which functionally increase the behavioral options of agents, but might also constrain their behavior when interacting with other agents beyond simple competitive interactions.

Model complexity is defined by the richness of model behavior at the system level. Complex behavior is the result of interconnected and non-reducible relationships between system components, often producing feedbacks and emergent states resulting from bottom-up interactions (Sun et al., in press). Thus, model complexity depends on the type and scope of interactions represented at each Level. In contrast to model complicatedness, model complexity is highest at mid-Level building-block processes and decreases at the highest and lowest Levels. This is because at the lowest Level, agents' behavioral options are limited due to relatively fewer agent-agent and agent-environment interactions. At the highest Level, group-level processes place additional constraints on agent interactions (e.g. conformity and defector punishment in *social norm formation*), thus reducing the range of possible model outcomes.

### 2.5.2. *Building-block processes*

We define *aspirations* as the level of social prestige, material well-being, wealth, or utility an agent attempts to achieve. Level 1 individual aspiration levels are defined as the maximum income that can be generated by the profit-maximizing mix of production and non-production livelihood

**Table 3.** Example individual and group traits that interact according to varying levels of 'building-block processes'. Process representation ranges from simple and generic (Level 1) to complicated and context dependent (Level 4).

| | | Building-block processes | | | | |
|---|---|---|---|---|---|---|
| | | Individual | | Group | | |
| Trait | | Aspiration formation | Risk perception | Land allocation | Social norm formation | Social networks influences |
| **Level** | 4 | *Level 3* + social norm regulated | *Level 3* + salience bias | *Level 3* + social norm regulated | *Level 3* + conformity + defector punishment | *Level 3* + centrality-based edge creation |
| | 3 | *Level 2* + social network influences | *Level 2* + loss aversion | *Level 2* + market exchange | *Level 2* + conditional cooperation + adoption rate dependent | *Level 2* + aspatial random |
| | 2 | *Level 1* + satisficing | Dynamic, subjective | *Level 1* + competitive expansion | *Level 1* + unconditional cooperation within social network | Link creation among immediate neighbors |
| | 1 | Profit-max | Objective | Random with land suitability | *None* | *None* |

choices. At minimum, aspiration levels equal subsistence needs. Level 2 introduces a basic satisficing model in which a specific level of attainment (e.g. subsistence needs) is achieved at minimum cost. This takes into account empirical evidence that aspirations may be subjective due to individual risk aversion of investing additional time and/or labor into livelihood activities (Ellis, 1993; Netting, 1993). Level 3 includes influences from social networks such that individual aspirations become tied to perceptions of wealth relative to other social group members (Bert et al., 2011; De Sherbinin et al., 2008; Key & Roberts, 2009). Further constraints may be placed on aspirations at Level 4 based on socio-economic stratification (Level 4; Dorward et al., 2009). At any level, individual agent traits and/or social influences may be such that aspirations align with profit-maximization, but higher building-block levels allow for more factors to intercede and cause aspirations to diverge from purely profit-maximizing levels.

*Risk perception* influences individual agents' expectations of potential returns and losses from livelihood activities, such as engaging in a specific land use, allocating labor to non-production purposes, or experimenting with a new technology. At Level 1, a full information and perfect rationality model is assumed, in which case expected probability of a risky event (e.g. stochastic rain reduction or price volatility) is equal to its objective probability. Level 2 introduces a dynamic risk perception in which expected probability is updated with new information from the agent's experiences (i.e. incomplete risk information) and can diverge from objective probabilities (e.g. Gallagher, 2014). Level 3 implements various cognitive biases toward loss aversion and the status quo, for example, as described by Prospect Theory (Kahneman, Knetsch, & Thaler, 1991; Kahneman & Tversky, 1979). Level 4 extends the cognitive bias to risk-seeking behavior using Salience Theory (Bordalo, Gennaioli, & Shleifer, 2010).

*Land allocation* processes are the means through which non-uniform distributions of territorial claims or land holdings occur. At Level 1, no social process for land allocation is assumed, and the size and quality of land holdings are randomly drawn from a distribution. Level 2 is the expansion of land holdings via non-market acquisition through direct competition for land patches (see *Competition*). Contests for occupied land patches are settled by comparative advantage, such as implemented in the generalized land change model CRAFTY (Murray-Rust et al., 2014). Presence and functioning of land markets are represented at Level 3 (e.g. Filatova, Parker, & Van Der Veen, 2009; Magliocca, Safirova, McConnell, & Walls, 2011; Parker & Filatova, 2008). Level 4 represents more complex land tenure rules, power imbalances, or other social institutions which may alter land allocation process beyond what would be predicted by individual competitiveness and free market exchange (Herrero et al., 2014).

*Social norms* are patterns of individual behaviors that are repeated by many individuals and reinforced by group selection (Axelrod, 1986). Two types of social norms are represented here that influence use of and access to natural resources, respectively: adoption of new land-use practices and cooperative behavior. The former can be modeled with the same mechanisms in established innovation diffusion models (e.g. Berger, 2001) in which innovative practices are first adopted by a small minority, followed by the 'mainstream' majority, and lastly by the reticent 'laggards' in a population. Cooperative behaviors are modeled as the frequency with which agents share resources and their reputation for doing so (see *Cooperation*), and is the prime mechanism for social group formation (see *Social groups*). The null model at Level 1 assumes that no social norms exist and all agents are 'innovators' (i.e. 'rational egoists'; Ostrom, 2000) that behave only in short-term self-interest. Social interactions consist only of competitive interactions. At Level 2, 'conformist' agents are added to the agent population, and norms form through agents simply mimicking the most successful livelihood strategies they observe within their social network (if present). Social interactions are characterized by unconditional cooperation within social networks (if present), and norms form through agents simply mimicking the most successful livelihood strategies they observe within their social network. Level 3 allows for all types of conformity traits with 'adopters' influenced by group adoption thresholds, via the 'bandwagon effect' (Secchi & Gullekson, 2016), or by comparing individual production

efficiency relative to new land management practices (see *Conformity*). Level 3 also introduces a collective action dynamic. Group formation becomes a possibility through social interactions of conditional cooperation (Ostrom, 2000), although the stability of groups depends on the proportion of cooperative relative to defector agents in the population. Level 4 introduces a mechanism by which groups or select members of groups (e.g. 'elites') can actively punish or otherwise reinforce social norms of cooperation and access to natural resources (e.g. Axelrod, 1986; Epstein, 2001; Janssen, Manning, & Udiani, 2013).

*Social network* interactions are often important for explaining adoption and diffusion dynamics of new land management practices (Manson, Jordan, Nelson, & Brummel, 2016), social norms of land management (Evans, Phanvilay, Fox, & Vogler, 2011), and subjective aspiration levels (Bert et al., 2011). Level 1 assumes that livelihood and land management strategies are not influenced by social networks, which could reflect low population densities or the overwhelming influence of environmental constraints and/or market forces over social interactions. Levels 2 and 3 consider the influences of non-spatial and spatial social interactions, respectively. At Level 4, new linkages (i.e. edges) in social networks can be formed with a probability related to node centrality and/or connectedness, consistent with the notion of social centrality in anthroecological theory (Equations (1) and (2) and Figure 2).

#### 2.5.3. *Submodels*

Submodels are not experimentally manipulated like building-block processes, but rather act as the templates through which specific mechanisms introduced by different building-block process levels operate.

**2.5.3.1. *Reproduction.*** New household agents use land patches according to land management strategy. If average annual production exceeds current subsistence demands, the agent reproduces to create a 'child' household of the same size (two adults, two children). 'Parent' agents reproduce at the end of the second decade (if resources are adequate) and are removed with increasing probability moving forward through simulated time. Remaining agents can continue to reproduce every subsequent decade if production levels are sufficiently high. 'Child' agents inherit the individual traits and social group affiliations of the 'parent' agents via direct replication, but with a low probability of variation in traits due to random mutation and/or cross-over using a genetic algorithm (e.g. Waring, Goff, & Smaldino, 2015).

**2.5.3.2. *Conformity.*** The likelihood that an agent will adopt a new land-use innovation is governed by the agent's conformity trait and the active setting of the *social norm formation* building-block process. Three types of conformity behavior are specified by the conformity trait: innovator, adopter, and conformist. Agents are aligned along a spectrum of conformity. At one end are 'innovators', which are more likely to experiment with new land management strategies and are less influenced by social norms. On the other end of the spectrum are 'conformers', which rarely experiment and conform to the social norm of land management practices. 'Adopters' will only adopt a new land management practice if the perceived marginal return on production of the new land management practice exceeds that of their current practice, subjective to individual risk preference, or a majority of other group members have adopted the new land management practice *and* there is no punishment for departing from social norms. These behavioral traits are consistent with established dynamics of innovation diffusion (e.g. Berger, 2001), and also account for dynamics of social norm formation and norm-using behaviors (e.g. Ostrom, 2000).

**2.5.3.3. *Cooperation.*** Agents can cooperate to share food and/or income resources within social groups and defend group members against competing agents from other social groups. Cooperation is modeled based on the concept of conditional cooperation (Ostrom, 2000) in which individuals will contribute resources to the public good when they expect others to

contribute and continue to contribute when other reciprocate (Janssen et al., 2013). Accepting resources from group members during times of scarcity due to environmental or market volatility is a way to smooth consumption (de Janvry et al., 1991), and is a means for long-term risk aversion for cooperators with the expectation for reciprocal sharing in the future. Individual agent cooperative behavior depends on the cooperation trait and the active setting of the *social norm formation* building-block process. At Levels 1, no agents cooperate ('share with no one' trait) and only individual selection and competition occurs (i.e. 'survival of the fittest'). At Level 2, unconditional cooperators ('always share' trait) are introduced into the agent population. Agent interactions resemble the onetime prisoner's dilemma game, because unconditional cooperators do not penalize defectors or change strategies. Emergence of cooperation depends on the relative proportion of cooperators and defectors in the agent population. Level 3 introduces conditional cooperators into the agent population. Conditional cooperation can occur within social groups subject to each agent's 'reputation', or past history of resource sharing. Agents observed to withhold resources in the past (i.e. defectors) may be excluded from resource sharing in the future based on low reputation. Level 4 introduces punishment of defectors by exacting a tax of resources, for example, which reinforces resource sharing and social norm following (see 'adopters' in *Conformity*).

**2.5.3.4. *Social groups.*** Groups formed by social interactions through social networks. Investment in social time is costly, as it reduces available time for other livelihood activities, and thus is allocated across different types of relationships that balance the costs of maintaining the relationship relative to the benefits gained from the relationship (Sutcliffe, Dunbar, & Wang, 2016). Groups emerge from interactions among individual agents with similar social characteristics, such as reputation for and degree of cooperation (i.e. resource sharing). Agents will tend to sort into groups with similar levels of resource sharing and tolerance for non-reciprocators (Ostrom, 2000). Within groups, member agents share or transmit social norms and reference points for subjective aspirations. Most importantly, groups regulate individual access to natural resources. Adherence to group norms of cooperation reaps the benefits of resource sharing, but divergence from cooperative norms can result in punishment and loss of group affiliation. Such defector punishment can maintain stable groups (Sutcliffe et al., 2016) and/or reinforce social structures of cooperation and access to natural resources (Sasaki et al., 2016).

**2.5.3.5. *Competition.*** Competition occurs when an agent attempts to expand beyond their current territorial claims or land area managed and/or owned. Two states can lead to expansion. If subsistence needs *or* aspirations are not met, agents attempt to expand territory/managed land area. If both conditions are satisfied, no expansion of territory/managed land area occurs. Expansion due to insufficient productivity is characteristic of low-intensity resource extraction societies (e.g. hunter-gatherer). Expansion due to unmet aspirations (i.e. for greater production) is characteristic of agrarian and industrial societies. The mechanism of expansion (e.g. forcible takeover, market acquisition, or top-down allocation) depends on the level of the *land allocation* building-block process. Preference for expansion is given to nearest vacant land patch, because removal of other agents is costly. If no vacant patches are available, then the nearest land patch occupied by an agent or agents of another social group and/or economic class is targeted. At level 1 of the *land allocation* building-block process, no competitive expansion occurs. Level 2 introduces bilateral competition for land patches. When an agent attempts to expand into an occupied land patch, the outcome is decided by comparing the *average* production level of the expanding versus resident. The production level of the resident agent depends on their average production level and cooperative status in their social group (*social norm formation* building-block process). If the agent has a reputation for previous cooperation, the average production level per capita of the *social group* is compared against the expanding agent's. In this way, the potential benefits of cooperation by sharing of resources are realized through potentially higher average production over time than

any individual's average production level. If the agent has a reputation for defection, social group support in defending their land patch is not available, and the agent's average production level is compared instead to the expanding agent's. The agent with higher average productivity occupies the land patch.

At Level 3, market exchange of land patches is introduced. In this setting, multiple agents can be competing for the same vacant land patch, and the highest bidder is awarded the land patch (e.g. Filatova et al., 2009; Magliocca et al., 2011; Parker & Filatova, 2008). If the land patch is occupied, the resident agent makes the decision to sell the land patch before ownership changes (i.e. no forced removal). The mechanism for land allocation represents the exercising of a competitive advantage (i.e. greater financial resources) without violence. Finally, Level 4 introduces land allocation mechanisms mediated by social structure. This includes market exchange, but with the explicit representation of power imbalances between buyers and sellers. The buyer or seller may have unequal influence on the exchange process, either through asymmetries in information or access (e.g. zoning laws that favor housing developers) (e.g. Magliocca, McConnell, Walls, & Safirova, 2012), or institutionalized control over the exchange mechanism (e.g. state-owned land, exercise of imminent domain).

**2.5.3.6. *Selection.*** Both individual- and group-level selection (Waring, Kline, et al., 2015) occurs within this modeling framework. Selection pressures originate from interactions between agent land management practices, social dynamics, and the environment. Agricultural practices that are consistent with land suitability constraints, such that levels of food and/or income-generating production are sufficient to meet subsistence needs and aspirations over the long term, provide an individual advantage in bilateral competition for land and contribute to elevating average social group productivity (i.e. fitness). Group-level traits, such as cooperation and social norms for adopting the best available land management practices, help reinforce successful strategies and improve the average fitness of individual group members during times of resource scarcity and/or competition from other social groups. Successful traits are propagated via vertical inheritance between 'parent' and 'child' households and horizontal transmission via social learning and group norms. Less efficient or unsustainable land management strategies are reproduced with low frequency or not at all. Thus, environmental and social forces select for land management strategies that optimize cultural and ecological inheritance over time.

## 3. Operationalization of the ABVL approach

Selecting which building blocks to include and at what levels of complexity to specify is challenging and an area of ongoing research. Here, we put forward a set of guiding questions for selecting building-block processes and their specification:

(1) What exogenous and endogenous selective pressures are acting on the evolution of land-use strategies (e.g. environmental constraints, agents' objective functions)? At what level are these selective pressures operating – individual, group, or society? What trajectories of sociocultural and landscape change are associated with these selective pressures?
(2) Which sociocultural traits for resource exploitation and the processes through which they interact with other traits are most salient for a given context and across contexts? Do these act additively or synergistically? Can a parsimonious set be defined? This will determine the levels of sophistication at which building blocks are specified and combinations in which they are implemented.
(3) Which environmental factors and processes contribute to human ecological inheritance? What are their characteristic rates of change and spatial boundaries and scale? The suite of environmental processes and their dynamics influence the nature of feedbacks from resource exploitation strategies and may favor or discourage cooperation, *sensu* the role

of resource system and unit characteristics in Ostrom's framework for common pool resource governance (e.g. Ostrom, 2007).

(4) Over what timescales do selective pressures operate? Depending on the dynamics of selective pressures, demographic changes may be more or less important relative to social learning in propagating successful traits.

Operationalizing this approach requires integration of a diversity of disciplinary perspectives to ensure building-block process selection and representation are grounded in theory, and when multiple theoretical explanations exist, leveraging this situation to compare candidate building blocks across a wide range of conditions.

## 4. Virtual lab implementation

Implementing the ABVL approach requires combined model parameterization, evaluation, and selection as part of an iterative modeling cycle (Figure 4). First, an evaluation technique must be defined to assess whether model parameterization and calibration are accurate. An evaluation technique is required that leads to not only outcome accuracy but also structural accuracy to reduce the chances of ecological fallacy in simulation-based explanations (NRC, 2014). Given the generalized model structure required for the building blocks modeling approach, high outcome accuracy should not be expected for any particular context, and thus conventional techniques based solely on quantitative agreement are not sufficient. On the other hand, a moderate degree of outcome accuracy is also important for linking improvements in model performance to the relative contribution of particular processes. Given these requirements, pattern-oriented modeling (POM; Grimm et al., 2005) offers the necessary balance between structural and predictive model evaluation. POM is an inverse modeling technique based on the premise that agreement between

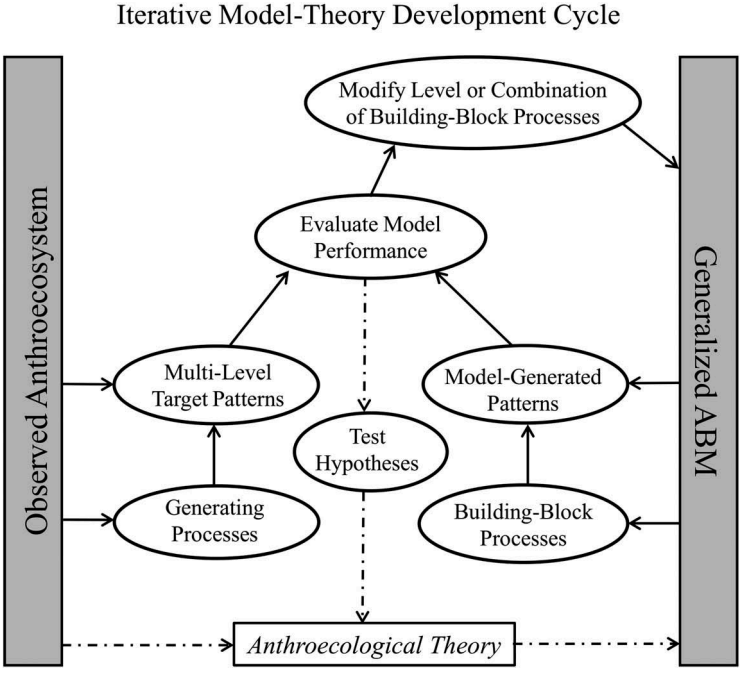


**Figure 4.** The iterative modeling cycle to improve model outcome and process accuracy using the pattern-oriented modeling (POM) approach. Real anthroecological system and modeled patterns are compared, errors assessed, new hypotheses of missing processes are formulated, and new levels and/or combinations of building-block processes are implemented.

multiple modeled and observed agent and/or system behaviors (i.e. process accuracy) can provide as much or more insight into the internal structure of the real system than a match between modeled and observed states (i.e. outcome accuracy). The main principle of POM is that a model with high outcome and process accuracy will reproduce multiple patterns observed in real systems, or 'target patterns', at different levels of system organization simultaneously. If a model can accomplish this, one can conclude that the model's process representation and internal structure are reasonably consistent with those of the real system (Grimm et al., 2005; Kramer-Schadt, Revilla, Wiegand, & Grimm, 2007).

A pattern is defined as 'any observation made at any hierarchical level or scale of the real system that displays non-random structure' (Kramer-Schadt et al., 2007, p. 1557). Target patterns should be linked to the expected outcomes of building-block processes, independent from calibration data, and not directly predictable by either micro- or macro-scale data (Latombe, Parrot, & Fortin, 2011). Target patterns could include: *landscape-level*: percent and/or distribution of land uses types; *population-level*: income distribution, poverty rates, land techno-managerial adoption rates, and/or livelihood diversity; *agent-level*: production and/or consumption levels associated with agent types (e.g. Murray-Rust et al., 2014; Valbuena, Verburg, & Bregt 2008). If available, comparing model dynamics to time series of one or more of these target patterns is an even more rigorous and challenging test of model realism.

Second, combining POM with evolutionary programming techniques, such as genetic algorithms, can efficiently search and evaluate a wide range of parameter and building-block process combinations (e.g. Magliocca, 2015). Here, we propose the use of a hierarchical genetic algorithm (HGA) for simultaneous parameter calibration and selection of building-block processes. For each model instantiation, a HGA specifies the levels of building-block processes to be implemented and the values of other uncertain model parameters (i.e. 'free parameters'). Free parameters describing environmental conditions and agent characteristics are randomly selected from distributions derived from primary data or literature. This genetic algorithm design is hierarchical in the sense that many free parameter values are explored for each combination of building-block process before selecting new building-block settings. Further, model instantiations that use higher level building-block processes are 'penalized', similar to Akaike Information Criterion (Akaike, 1974), so that higher level building-block process settings must appreciably improve model performance to remain active. Environmental conditions are parameterized with localized values for a given simulation site from the global data sources listed in Table 2. Parameter distributions for agent characteristics, such as risk preferences, are informed by values from case study literature, if available, or are allowed to vary freely with each model instantiation. All agents are initialized with the least intensive available land management strategy. Available land-use options are based on land suitability constraints and experimental levels of agricultural technologies as specified by the modeler. The performance of each model instantiation is evaluated using POM, the next generation of building-block settings and parameter values are specified by the HGA, and additional model simulations are performed until all target patterns are satisfactorily reproduced in model outcomes.

While this iterative modeling approach is likely to improve model performance with successive generations of the HGA, the possibility remains that multiple different model configurations could successfully reproduce all target patterns (i.e. 'equifinality'), making it difficult to adjudicate among model versions. Equifinality of complex systems is a challenge for all non-deterministic modeling approaches (NRC, 2014). We will not solve this issue here. However, the POM approach sets an exceptionally high bar for empirical model validation – more so than conventional, single-scale measurement approaches. Thus, rigorous POM methods combined with the HGA approach can minimize the possibility of equifinality in model configurations.

## 5. Case narratives

To illustrate how the building-block processes approach can be implemented, two case narratives drawn from the empirical land change case study literature are described using the ABVL framework. We provide the details associated with the guiding questions in Section 3, specify target patterns for model evaluation with POM as described in Section 4, and hypothesize likely building-block process combinations for each case (Table 4). The first case describes the evolution of collective farming practices and creation of mosaic landscapes in northern Laos during and after the Second Indochina War (approx. 1960s through 1990s) and is drawn from Castella et al. (2013). The second case describes the adaptive land-use and livelihood responses of agricultural households in southwestern Tanzania to economic liberalization policies occurring from the 1980s to early 2000s and is drawn from Grogan, Birch-Thomsen, and Lyimo (2013). These example cases were chosen because they share similar biophysical settings and land-use practices, but describe different trajectories of sociocultural and landscape change.

Both cases describe land-use and livelihood dynamics in and around agricultural villages of less than 50 persons $km^{-2}$ during the time periods of interest, and both locations shared similar environmental conditions and associated selective pressures on land-use practices. Tropical climates allowed for long growing seasons, rain-fed agriculture (>1000 mm annual precipitation), and relatively quick forest regeneration, but also increased risk of pest damages and limited soil fertility. The terrain in both locations was fairly mountainous making intensive cultivation difficult in portions of the landscape. Shifting cultivation was the dominant land-use practice, and involved culturally inherited practices of forest clearing, burning, and infrequent sowing and harvesting. Continual cultivation of land patches without external inputs typically was susceptible to yield declines in two to three seasons (Siebert & Döll, 2010; Tiessen, Salcedo, & Sampaio, 1992). Intensive cultivation was done with animal draught and/or hand hoe, and required application of fertilizer and higher labor inputs for sowing, weeding, and harvesting than shifting cultivation. Water was relatively accessible, but access to markets was limited to regional markets as the main opportunities for market exchange. Given these similarities, the same data was extracted from both case studies describing household-, population-, and landscape-level patterns for use with POM model evaluation: (1) distribution of land uses and covers; (2) livelihood and market-oriented production participation rates; (3) presence of a 'normal surplus' in agricultural production (de Janvry et al., 1991), (2) meeting or exceeding minimum aspiration levels (Turner & Ali, 1996), and (3) consumption smoothing (de Janvry et al., 1991). A detailed description of each of these patterns is available in Magliocca (2015).

### 5.1. *Northern Laos*

Land-use and sociocultural transitions in northern Laos during the early and mid-1960s were characterized by the creation of landscape mosaics and development of collective farming strategies brought on by external conflict. Peasants fleeing the conflicts of the Second Indochina War sought refuge in remote forested regions, where abundant land resources and external threat created favorable conditions for cooperation and social group formation. Inhabitants worked together to clear large tracts of land for collective farming, which created mosaics of low-intensity cultivated patches interspersed with forest and long fallow patches with regenerating forest (Castella et al., 2013). With relatively low population densities and abundant land, sufficient fallow times were possible to maintain soil fertility. Although cooperative land clearing imposed additional costs on individual or household subsistence strategies, these costs were outweighed by benefits of cooperation in light of strong group-level selection pressures. The cooperative cropping system 'facilitated the exchange of labor, made arduous work more congenial (e.g., weeding), spread the risk of pest damages over large fields and prevented insecurity at a time of political trouble' (Castella et al., 2013, p. 68).

**Table 4.** Hypothetical example building-block processes for the landscape and sociocultural transitions described for the Laos and Tanzania case narratives. Each society is described by potential combinations of building-block processes constituting culture.

| | Building-block processes | | | | |
|---|---|---|---|---|---|
| | Individual | | Group | | |
| Case study | Aspiration formation | Risk perception | Land allocation | Social norm formation | Social networks influences |
| Laos cooperative land use | *Level 2:* Level 1 + satisficing | *Level 3*: Level 2 + loss aversion | *Level 4:* Level 3 + social norm regulated | *Level 2: Level 1* + unconditional cooperation within social network | *Level 2*: Link creation among immediate neighbors |
| Tanzania economic liberalization | *Level 1:* Profit-maximizing | *Level 4*: Level 3 + salience bias | *Level 3*: Level 2 + market exchange | *Level 1*: None | *Level 3*: Level 2 + aspatial random |

A series of hypotheses about the underlying mechanisms of these sociocultural and landscape transitions can be tested with the ABVL. For example, external conflict combined with environmental conditions selected for social norms of cooperation and shifting cultivation land-use practices. These traits caused an expansion of cultivated and decrease of forested patches creating a mosaic landscape structure. Further, given the multi-decade time span and relatively homogeneous livelihood strategies and wealth of this subsistence regime, the main mechanism of sociocultural evolution was primarily through cross-generational inheritance (i.e. vertical transmission) of traits, rather than other social learning processes or interaction with exogenous sociocultural influences. The specific building-block processes hypothesized to generate these social interactions and landscape structure are shown in Table 4. Aspiration formation and risk perception processes are strongly influenced by loss aversion at the individual level, and group-level processes of land allocation, social norm formation, and social network influences favor the evolution of self-reinforcing, highly cooperative groups composed of kin and/or spatially proximate individuals or households.

### 5.2. *Southwestern Tanzania*

Land-use and sociocultural transitions in southwestern Tanzania during the 1980s to early 2000s consisted of the abandonment of intensive maize cultivation for traditional shifting cultivation techniques. This transition was brought about by state policies of economic liberalization that removed previous subsidies for fertilizer and improved seed varieties (Grogan et al., 2013). Individual-level selective pressures on land-based production and livelihood sustainability, which were once alleviated (at least partially) by agricultural subsidies program, were renewed when subsidies were removed. Without subsidies, fertilizer and seed costs made maize cultivation unprofitable for many. A number of substantial sociocultural changes resulted (see Grogan et al., 2013 for more details). Responses among agricultural households were varied, but an overall trend of agricultural extensification with a return to traditional shifting cultivation, limited fallow times leading to soil degradation, withdrawal from commodity markets, and expansion of off-farm livelihoods (Birch-Thomsen & Fog, 1996). Those that still cultivated maize or switched to cash crops replaced traditional social work groups with paid labor. Households with cross-border kin and social network connections saw well-being improvements through non-farm income opportunities. Expanding agriculture increased land disputes, but local authority mediation mechanisms persisted through customary land rights. These sociocultural changes also translated into dramatic landscape alterations. Reduced cultivation intensity led to a large reduction in fertilizer use (13–42%), and expansion of low-intensity farming shortened time for miombo woodland regeneration and increased clearing of forests (Grogan et al., 2013).

This case is ideal for testing the influence of social learning processes on responses to economic liberalization and subsequent sociocultural and landscape transitions. Specific hypotheses to test with the ABVL might focus on mechanisms of increasing aspirations, economic differentiation, and social connectedness. For example, the loss of agricultural subsidies shifted the dominant selective pressure from the state to the household, which selected for competitive individual strategies and the formation of social networks of economic opportunities. Hypothesized associated landscape changes would include expansion of cultivated area (with loss of forest cover) to compensate for soil degradation, and abandonment of marginal land as households shift to non-farm livelihoods. Further, introduction of mimicking of successful livelihood strategies (both farm and non-farm) among social network influences would increase livelihood strategy diversity and economic differentiation. The specific building-block processes hypothesized to generate these transitions are shown in Table 4. Aspiration formation and risk perception processes favor profit-maximization and risk-tolerant livelihood strategies at the individual level, and group-level processes of land allocation, social norm formation, and social network are characteristic of market-mediated social interactions. In this case, removal of subsidies selected against social norms (e.g. work groups, agricultural cooperatives) in favor of market institutions.

## 6. Conclusions

This article is the first to explore the potential of generalized ABMs (Magliocca, 2015) to simulate and test the newly articulated evolutionary principles and hypotheses of anthroecological theory as explanations for observed patterns of coupled social and landscape change (Ellis, 2015). This potential has been demonstrated through an initial prospective example of how a formal, explicit, mechanistic specification of SNC theory might be implemented with an ABVL approach to simulate and test hypotheses on long-term anthroecological changes across different geographic settings and society types. This effort to close the gap between theoretical and mechanistic explanations of coupled sociocultural and landscape changes over evolutionary time periods has forced a working through of the dynamic implications of the ABM specification, which has theory-building value in and of itself (Poile & Safayeni, 2016; Weinhardt & Vancouver, 2012).

The ABVL experimental approach has shown clear potential to formalize and test SNC as a long-term evolutionary process linking landscape and sociocultural change – moving from empirical to mechanistic understanding – and ultimately improving theory. Building-block processes are especially useful in this effort, as they enable systematic exploration of how individual and group traits generate and/or interact with the structuring factors of anthroecology theory – biome, society type, and patterns of social centrality and land suitability – to produce plausible and empirically testable patterns of populations, land use, and ecological processes across landscapes. While the use of simple ABMs as virtual laboratories to evaluate competing theories of emergent phenomenon is not new (Batty & Torrens, 2001; Grimm & Berger, 2016; Janssen & Ostrom, 2006; O'Sullivan et al., 2016), the ability to experimentally introduce a suite of generalized sociocultural evolutionary mechanisms in various combinations and subjected to different social and environmental contexts is novel.

Comprehensive theory development in LSS has always required an understanding of the coevolution of social and ecological systems. A general, mechanistic, model of land transformation across the full spectrum of human societies and environments represents a grand challenge for LSS and a turn toward a 'generative social science' mode of inquiry. Fundamental to this challenge is the need to balance simplicity and flexibility of process representation with sufficient realism to enable comparisons with empirical data. Here we have proposed to advance LSS theory by an ABVL approach that enables experimenting with and building basic models that strip away detail in an effort to reveal something akin to 'first principles' of human–environment interactions (Grimm & Berger, 2016). We have shown that the ABVL approach offers unprecedented opportunity for formalizing, operationalizing, and testing of theoretical predictions. We also presented a 'roadmap' for combining general theories on the structure and dynamics of human–environment interactions with generic, mechanistically rich ABMs to support theory development and the testing of hypotheses against empirical data. Our hope is that this approach renews interest in theory-based models of cultural landscape change, and ultimately strengthens our ability to understand and manage the unprecedented land system changes now developing as Earth moves deeper into the Anthropocene.

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## References

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*, *19*(6), 716–723. doi:10.1109/TAC.1974.1100705

An, L. (2012). Modeling human decisions in coupled human and natural systems: Review of agent-based models. *Ecological Modelling*, *229*, 25–36. doi:10.1016/j.ecolmodel.2011.07.010

Arthur, W. B. (1994). Inductive reasoning and bounded rationality. *The American Economic Review*, *84*(2), 406–411. Retrieved from http://www.jstor.org/stable/2117868

Arthur, W. B., Durlauf, S., & Lane, D. (1997). *The economy as an evolving complex system II*. Sante Fe, NM: Addison-Wesley.

Axelrod, R. (1986). An evolutionary approach to norms. *American Political Science Review*, *80*, 1095–1111. doi:10.1017/S0003055400185016

Batty, M., & Torrens, P. M. (2001). Modeling complexity: The limits to prediction. *Cybergeo: European Journal of Geography*, *201*. doi:10.4000/cybergeo.1035

Berger, T. (2001). Agent-based spatial models applied to agriculture: A simulation tool for technology diffusion, resource use changes and policy analysis. *Agricultural Economics*, *25*(2–3), 245–260. doi:10.1111/j.1574-0862.2001.tb00205.x

Bert, F. E., Podestá, G. P., Rovere, S. L., Menéndez, Á. N., North, M., Tatara, E., … Toranzo, F. R. (2011). An agent based model to simulate structural and land use changes in agricultural systems of the argentine pampas. *Ecological Modelling*, *222*(19), 3486–3499. doi:10.1016/j.ecolmodel.2011.08.007

Bettencourt, L. M. A. (2013). The origins of scaling in cities. *Science*, *340*(6139), 1438–1441. doi:10.1126/science.1235823

Birch-Thomsen, T., & Fog, B. (1996). Changes within small-scale agriculture – A case-study from the southwestern Tanzania. *Danish Journal of Geography*, *96*, 60–69. doi:10.1080/00167223.1996.10649377

Boivin, N. L., Zeder, M. A., Fuller, D. Q., Crowther, A., Larson, G., Erlandson, J. M., … Petraglia, M. D. (2016). Ecological consequences of human niche construction: Examining long-term anthropogenic shaping of global species distributions. *Proceedings of the National Academy of Sciences*, *113*(23), 6388–6396. doi:10.1073/pnas.1525200113

Bordalo, P., Gennaioli, N., & Shleifer, A. (2010). Salience theory of choice under risk. National Bureau of Economic Research. Retrieved from http://www.nber.org/papers/w16387

Boserup, E. (1965). *The conditions of agricultural growth: The economics of agrarian change under population pressure*. Chicago, IL: Aldine.

Boyd, R., Richerson, P. J., & Henrich, J. (2011). The cultural niche: Why social learning is essential for human adaptation. *Proceedings of the National Academy of Sciences*, *108*(Supplement 2), 10918–10925. doi:10.1073/pnas.1100290108

Brown, D. G., Aspinall, R., & Bennett, D. (2006). Landscape models and explanation in landscape ecology – A space for generative landscape science? *The Professional Geographer*, *58*, 369–382. doi:10.1111/j.1467-9272.2006.00575.x

Brown, D. G., Verburg, P. H., Pontius, R. G., Jr., & Lange, M. D. (2013). Opportunities to improve impact, integration, and evaluation of land change models. *Current Opinion in Environmental Sustainability*, *5*, 452–457. doi:10.1016/j.cosust.2013.07.012

Brughmans, T. (2013). Thinking through networks: A review of formal network methods in archaeology. *Journal of Archaeological Method and Theory*, *20*(4), 623–662. doi:10.1007/s10816-012-9133-8

Butzer, K. W. (1982). *Archaeology as human ecology: Method and theory for a contextual approach*. New York, NY: Cambridge University Press.

Castella, J.-C., Lestrelin, G., Hett, C., Bourgoin, J., Fitriana, Y. R., Heinimann, A., & Pfund, J.-L. (2013). Effects of landscape segregation on livelihood vulnerability: Moving from extensive shifting cultivation to rotational agriculture and natural forests in northern Laos. *Human Ecology*, *41*, 63–76. doi:10.1007/s10745-012-9538-8

Christaller, W. (1933). *Die zentralen Orte in Süddeutschland. Eine ökonomisch geographische Untersuchung über die Gesetzmäßigkeit der Verbreitung und Entwicklung der Siedlungen mit städtischen Funktionen*. Ann Arbor, MI: University Microfilms.

Cottineau, C., Chapron, P., & Reuillon, R. (2015). Growing models from the bottom up. An evaluation-based incremental modelling method (EBIMM) applied to the simulation of systems of cities. *Journal of Artificial Societies and Social Simulation*, *18*(4), 9. doi:10.18564/jasss.2828

Danchin, É. (2013). Avatars of information: Towards an inclusive evolutionary synthesis. *Trends in Ecology & Evolution*, *28*(6), 351–358. doi:10.1016/j.tree.2013.02.010

Danchin, É., Charmantier, A., Champagne, F. A., Mesoudi, A., Pujol, B., & Blanchet, S. (2011). Beyond DNA: Integrating inclusive inheritance into an extended theory of evolution. *Nature Reviews Genetics*, *12*, 475–486. doi:10.1038/nrg3028

de Janvry, A., Fafchamps, M., & Sadoulet, E. (1991). Peasant household behaviour with missing markets: Some paradoxes explained. *The Economic Journal*, *101*(409), 1400–1417. doi:10.2307/2234892

De Sherbinin, A., VanWey, L. K., McSweeney, K., Aggarwal, R., Barbieri, A., Henry, S., … Walker, R. (2008). Rural household demographics, livelihoods and the environment. *Global Environmental Change*, *18*(1), 38–53. doi:10.1016/j.gloenvcha.2007.05.005

Dorward, A., Anderson, S., Bernal, Y. N., Vera, E. S., Rushton, J., Pattison, J., & Paz, R. (2009). Hanging in, stepping up and stepping out: Livelihood aspirations and strategies of the poor. *Development in Practice*, *19*(2), 240–247. doi:10.1080/09614520802689535

Dyball, R., & Newell, B. (2014). *Understanding human ecology: A systems approach to sustainability*. New York, NY: Routledge.

Dyble, M., Salali, G. D., Chaudhary, N., Page, A., Smith, D., Thompson, J., … Migliano, A. B. (2015). Sex equality can explain the unique social structure of hunter-gatherer bands. *Science*, *348*(6236), 796–798. doi:10.1126/science.aaa5139

Eerkens, J., & Lipo, C. (2007). Cultural transmission theory and the archaeological record: Providing context to understanding variation and temporal changes in material culture. *Journal of Archaeological Research*, *15*, 239–274. doi:10.1007/s10814-007-9013-z

Ellis, E. C. (2015). Ecology in an anthropogenic biosphere. *Ecological Monographs*, *85*, 287–331. doi:10.1890/14-2274.1

Ellis, E. C., & Ramankutty, N. (2008). Putting people in the map: Anthropogenic biomes of the world. *Frontiers in Ecology and the Environment*, *6*, 439–447. doi:10.1890/070062

Ellis, F. (1993). *Peasant economics: Farm households and agrarian development*. Cambridge: Cambridge University Press.

Epstein, J. M. (1999). Agent-based computational models and generative social science. *Complexity*, *4*(5), 41–60. doi:10.1002/(ISSN)1099-0526

Epstein, J. M. (2001). Learning to be thoughtless: Social norms and individual competition. *Computational Economics*, *18*, 9–24. doi:10.1023/A:1013810410243

Epstein, J. M. (2002). Modeling civil violence: An agent-based computational approach. *Proceedings of the National Academy of Sciences*, *99*(suppl 3), 7243–7250. doi:10.1073/pnas.092080199

Evans, T. P., Manire, A., de Castro, F., Brondizio, E., & McCracken, S. (2001). A dynamic model of household decision-making and parcel level landcover change in the eastern Amazon. *Ecological Modelling*, *143*, 95–113. doi:10.1016/S0304-3800(01)00357-X

Evans, T. P., Phanvilay, K., Fox, J., & Vogler, J. (2011). An agent-based model of agricultural innovation, land-cover change and household inequality: The transition from swidden cultivation to rubber plantations in Laos PDR. *Journal of Land Use Science*, *6*(2–3), 151–173. doi:10.1080/1747423X.2011.558602

Filatova, T., Parker, D., & Van der Veen, A. (2009). Agent-based urban land markets: Agent's pricing behavior, land prices and urban land use change. *Journal of Artificial Societies and Social Simulation*, *12*(1), 3. Retrieved from http://jasss.soc.surrey.ac.uk/12/1/3.html

Folke, C., Colding, J., & Berkes, F. (2003). Synthesis: Building resilience and adaptive capacity in social-ecological systems. In F. Berkes, J. Colding, & C. Folke (Eds.), *Navigating social-ecological systems: Building resilience for complexity and change* (pp. 352–387). Cambridge: Cambridge University Press.

Fuentes, A. (2016). The extended evolutionary synthesis, ethnography, and the human niche: Toward an integrated anthropology. *Current Anthropology*, *57*, SS13–SS26. doi:10.1086/685684

Gallagher, J. (2014). Learning about an infrequent event: Evidence from flood insurance take-up in the United States. *American Economic Journal: Applied Economics*, *6*(3), 206–233. doi:10.1257/app.6.3.206

Giddens, A. (2013). *The constitution of society: Outline of the theory of structuration*. Cambridge: Wiley.

Global Agro-Ecological Zones. (2011a). Terrain constraints. Retrieved June 6, 2011, from http://www.iiasa.ac.at/Research/LUC/GAEZ/index.htm

Global Agro-Ecological Zones. (2011b). Agro-climatic constraints. Retrieved June 6, 2011, from http://www.iiasa.ac.at/Research/LUC/GAEZ/index.htm

Grimm, V., & Berger, U. (2016). Structural realism, emergence, and predictions in next-generation ecological modelling: Synthesis from a special issue. *Ecological Modelling*, *326*, 177–187. doi:10.1016/j.ecolmodel.2016.01.001

Grimm, V., Berger, U., DeAngelis, D. L., Polhill, J. G., Giske, J., & Railsback, S. F. (2010). The ODD protocol: A review and first update. *Ecological Modelling*, *221*(23), 2760–2768. doi:10.1016/j.ecolmodel.2010.08.019

Grimm, V., Revilla, E., Berger, U., Jeltsch, F., Mooij, W. M., & DeAngelis, D. L. (2005). Pattern-oriented modeling of agent-based complex systems: Lessons from ecology. *Science*, *310*(5750), 987–991. doi:10.1126/science.1116681

Grogan, K., Birch-Thomsen, T., & Lyimo, J. (2013). Transition of shifting cultivation and its impact on people's livelihoods in the Miombo woodlands of northern Zambia and south-western Tanzania. *Human Ecology*, *41*, 77–92. doi:10.1007/s10745-012-9537-9

Håkansson, N. T., & Widgren, M. (2014). *Landesque capital: The historical ecology of enduring landscape modifications*. New York, NY: Left Coast Press.

Hamilton, M. J., Milne, B. T., Walker, R. S., & Brown, J. H. (2007). Nonlinear scaling of space use in human hunter-gatherers. *Proceedings of the National Academy of Sciences USA*, *104*(11), 4765–4769. doi:10.1073/pnas.0611197104

Hedström, P., & Ylikoski, P. (2010). Causal mechanisms in the social sciences. *Annual Review of Sociology*, *36*, 49–67. doi:10.1146/annurev.soc.012809.102632

Henrich, J. (2015). *The secret of our success: How culture is driving human evolution, domesticating our species, and making us smarter*. Princeton, NJ: Princeton University Press.

Henrich, J., Boyd, R., Bowles, S., Camerer, C., Fehr, E., Gintis, H., & Tracer, D. (2005). "Economic man" in cross-cultural perspective: Behavioral experiments in 15 small-scale societies. *Behavioral and Brain Sciences*, *28*, 795–855. doi:10.1017/S0140525X05000142

Herrero, M., Thornton, P. K., Bernués, A., Baltenweck, I., Vervoort, J., van de Steeg, J., … Staal, S. J. (2014). Exploring future changes in smallholder farming systems by linking socio-economic scenarios with regional and household models. *Global Environmental Change*, *24*, 165–182. doi:10.1016/j.gloenvcha.2013.12.008

Hill, K., Barton, M., & Hurtado, A. M. (2009). The emergence of human uniqueness: Characters underlying behavioral modernity. *Evolutionary Anthropology: Issues, News, and Reviews*, *18*, 187–200. doi:10.1002/evan.20224

Jackson, S. T. (2009). Alexander von Humboldt and the general physics of the earth. *Science*, *324*, 596–597. doi:10.1126/science.1171659

Jain, M., Naeem, S., Orlove, B., Modi, V., & DeFries, R. S. (2015). Understanding the causes and consequences of differential decision-making in adaptation research: Adapting to a delayed monsoon onset in Gujarat, India. *Global Environmental Change*, *31*, 98–109. doi:10.1016/j.gloenvcha.2014.12.008

Janssen, M. A., Manning, M., & Udiani, O. (2013). Evolution of conditional cooperation (Version 2). CoMSES Computational Model Library. Retrieved from http://hdl.handle.net/2286.0/oabm.3887

Janssen, M. A., & Ostrom, E. (2006). Empirically based, agent-based models. *Ecology and Society*, *11*(2), 37.

Kahneman, D., Knetsch, J., & Thaler, R. (1991). Anomalies: The endowment effect, loss aversion, and status quo bias. *Journal of Economic Perspectives*, *5*, 193–206. doi:10.1257/jep.5.1.193

Kahneman, D., & Tversky, A. (1979). Prospect theory: An analysis of decision under risk. *Econometrica*, *47*, 263–291. doi:10.2307/1914185

Key, N., & Roberts, M. J. (2009). Nonpecuniary benefits to farming: Implications for supply response to decoupled payments. *American Journal of Agricultural Economics*, *91*(1), 1–18. doi:10.1111/j.1467-8276.2008.01180.x

Kirch, P. V. (2005). Archaeology and global change: The Holocene record. *Annual Review of Environment and Resources*, *30*, 409–440. doi:10.1146/annurev.energy.29.102403.140700

Klein Goldewijk, K., & Ramankutty, N. (2004). Land cover change over the last three centuries due to human activities: The availability of new global data sets. *GeoJournal*, *61*(4), 335–344. doi:10.1007/s10708-004-5050-z

Kramer-Schadt, S., Revilla, E., Wiegand, T., & Grimm, V. (2007). Patterns for parameters in simulation models. *Ecological Modelling*, *204*, 553–556. doi:10.1016/j.ecolmodel.2007.01.018

Laland, K. N., Uller, T., Feldman, M. W., Sterelny, K., Müller, G. B., Moczek, A., … Odling-Smee, J. (2015). The extended evolutionary synthesis: Its structure, assumptions and predictions. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1813), 20151019. doi:10.1098/rspb.2015.1019

Latombe, G., Parrot, L., & Fortin, D. (2011). Levels of emergence in individual based models: Coping with scarcity of data and pattern redundancy. *Ecological Modelling*, *222*, 1557–1568. doi:10.1016/j.ecolmodel.2011.02.020

Levin, S., Xepapadeas, T., Crépin, A.-S., Norberg, J., de Zeeuw, A., & Walker, B. (2013). Social-ecological systems as complex adaptive systems: Modeling and policy implications. *Environment and Development Economics*, *18*, 111–132. doi:10.1017/S1355770X12000460

Levin, S. A., & Clark, W. C. (2010). *Toward a science of sustainability*. Warrenton, VA: The National Science Foundation, Airlie Center.

Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., & Zhu, C. (2013). Framing sustainability in a telecoupled world. *Ecology and Society*, *18*(2), 26. doi:10.5751/ES-05873-180226

Macmillan, W., & Huang, H. Q. (2008). An agent-based simulation model of a primitive agricultural society. *Geoforum*, *39*, 643–658. doi:10.1016/j.geoforum.2007.07.011

Macy, M. W., & Willer, R. (2002). From factors to factors: Computational sociology and agent-based modeling. *Annual Review of Sociology*, *28*, 143–166. doi:10.1146/annurev.soc.28.110601.141117

Magliocca, N., McConnell, V., Walls, M., & Safirova, E. (2012). Zoning on the urban fringe: Results from a new approach to modeling land and housing markets. *Regional Science and Urban Economics*, *42*(1–2), 198–210. doi:10.1016/j.regsciurbeco.2011.08.012

Magliocca, N., Safirova, E., McConnell, V., & Walls, M. (2011). An economic agent-based model of coupled housing and land markets (CHALMS). *Computers, Environment and Urban Systems*, *35*(3), 183–191. doi:10.1016/j.compenvurbsys.2011.01.002

Magliocca, N. R. (2015). Model-based synthesis of locally contingent responses to global market signals. *Land*, *4*(3), 807–841. doi:10.3390/land4030807

Magliocca, N. R., Brown, D. G., & Ellis, E. C. (2013). Exploring agricultural livelihood transitions with an agent-based virtual laboratory: Global forces to local decision-making. *PLoS One*, *8*(9), e73241. doi:10.1371/journal.pone.0073241

Magliocca, N. R., Brown, D. G., & Ellis, E. C. (2014). Cross-site comparison of land-use decision-making and its consequences across land systems with a generalized agent-based model. *PLoS One*, *9*(1), e86179. doi:10.1371/journal.pone.0086179

Magliocca, N. R., & Ellis, E. C. (2013). Using pattern-oriented modeling (POM) to cope with uncertainty in multi-scale agent-based models of land change. *Transactions in GIS*, *17*(6), 883–900. doi:10.1111/tgis.12012

Manson, S. M., Jordan, N. R., Nelson, K. C., & Brummel, R. F. (2016). Modeling the effect of social networks on adoption of multifunctional agriculture. *Environmental Modelling & Software*, *75*, 388–401. doi:10.1016/j.envsoft.2014.09.015

Marsh, G. P. (1865). *Man and nature: Or, physical geography as modified by human action*. New York, NY: Scribner.

Mesoudi, A. (2011). *Cultural evolution: how Darwinian theory can explain human culture and synthesize the social sciences*. Chicago, IL: University of Chicago Press.

Mesoudi, A., Whiten, A., & Laland, K. N. (2006). Towards a unified science of cultural evolution. *Behavioral and Brain Sciences*, *29*, 329–347. doi:10.1017/S0140525X06009083

Meyfroidt, P. (2015). Approaches and terminology for causal analysis in land systems science. *Journal of Land Use Science*, 1–27. doi:10.1080/1747423X.2015.1117530

Monfreda, C., Ramankutty, N., & Foley, J. (2008). Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary productivity in the year 2000. *Global Biogeochem Cy*, *22*, GB1022. doi:10.1029/2007GB002947

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., … Schwarz, N. (2013). Describing human decisions in agent-based models–ODD+ D, an extension of the ODD protocol. *Environmental Modelling & Software*, *48*, 37–48. doi:10.1016/j.envsoft.2013.06.003

Murray-Rust, D., Brown, C., van Vliet, J., Alam, S. J., Robinson, D. T., Verburg, P. H., & Rounsevell, M. (2014). Combining agent functional types, capitals and services to model land use dynamics. *Environmental Modelling & Software*, *59*, 187–201. doi:10.1016/j.envsoft.2014.05.019

National Research Council. (2014). *Advancing land change modeling: Opportunities and research requirements*. Washington, DC: National Academies Press.

Netting, R. (1993). *Smallholders, householders: Farm families and the ecology of intensive, sustainable agriculture* (pp. 9–447). Palo Alto, CA: Stanford University Press.

O'Sullivan, D., Evans, T., Manson, S., Metcalf, S., Ligmann-Zielinska, A., & Bone, C. (2016). Strategic directions for agent-based modeling: Avoiding the YAAWN syndrome. *Journal of Land Use Science*, *11*(2), 177–187. doi:10.1080/1747423X.2015.1030463

O'Sullivan, D., & Perry, G. L. (2013). *Spatial simulation: Exploring pattern and process*. West Sussex: John Wiley & Sons.

Odling-Smee, F. J., Laland, K. N., & Feldman, M. W. (2003). *Niche construction: The neglected process in evolution*. Princeton, NJ: Princeton University Press.

Ostrom, E. (2000). Collective action and the evolution of social norms. *Journal of Economic Perspectives*, *14*(3), 137–158. doi:10.1257/jep.14.3.137

Ostrom, E. (2007). A diagnostic approach for going beyond panaceas. *Proceedings of the National Academy of Sciences*, *104*(39), 15181–15187. doi:10.1073/pnas.0702288104

Parker, D. C., & Filatova, T. (2008). A conceptual design for a bilateral agent-based land market with heterogeneous economic agents. *Computers, Environment and Urban Systems*, *32*, 454–463. doi:10.1016/j.compenvurbsys.2008.09.012

Penning De Vries, F. W. T., Rabbinge, R., & Groot, J. J. R. (1997). Potential and attainable food production and food security in different regions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *352*, 917–928. doi:10.1098/rstb.1997.0071

Platt, J. R. (1964). Strong inference. *Science*, *146*(3642), 347–353. doi:10.1126/science.146.3642.347

Poile, C., & Safayeni, F. (2016). Using computational modeling for building theory: A double edged sword. *Journal of Artificial Societies and Social Simulation*, *19*(3), 8. doi:10.18564/jasss.3137

Richerson, P., Baldini, R., Bell, A., Demps, K., Frost, K., Hillis, V., … Zefferman, M. (2016). Cultural group selection plays an essential role in explaining human cooperation: A sketch of the evidence. *Behavioral and Brain Sciences*, *39*, e30.

Richerson, P. J., & Boyd, R. (2005). *Not by genes alone: How culture transformed human evolution*. Chicago, IL: University of Chicago Press.

Rivers, R., Knappett, C., & Evans, T. (2013). What makes a site important? Centrality, gateways and gravity. In C. Knappett (Ed.), *Network analysis in archaeology: New approaches to regional interaction* (p. 125). Oxford: Oxford University Press.

Roth, A. E., & Erev, I. (1995). Learning in extensive-form games: Experimental data and simple dynamic models in the intermediate term. *Games and Economic Behavior*, *8*(1), 164–212. doi:10.1016/S0899-8256(05)80020-X

Rounsevell, M. D. A., Arneth, A., Alexander, P., Brown, D. G., de Noblet-Ducoudré, N., Ellis, E. … Young, O. (2014). Towards decision-based global land use models for improved understanding of the earth system. *Earth System Dynamics*, *5*(1), 117–137. doi:10.5194/esd-5-117-2014

Sasaki, T., Penick, C. A., Shaffer, Z., Haight, K. L., Pratt, S. C., & Liebig, J. (2016). A simple behavioral model predicts the emergence of complex animal hierarchies. *The American Naturalist*, *187*(6), 765–775. doi:10.1086/686259

Schelling, T. C. (1971). Dynamic models of segregation. *Journal of Mathematical Sociology*, *1*(2), 143–186.

Scoones, I. (2009). Livelihoods perspectives and rural development. *The Journal of Peasant Studies*, *36*(1), 171–196. doi:10.1080/03066150902820503

Secchi, D., & Gullekson, N. L. (2016). Individual and organizational conditions for the emergence and evolution of bandwagons. *Computational and Mathematical Organization Theory*, 1–46. doi:10.1007/s10588-015-9199-4

Sen, A. K. (1959). The choice of agricultural techniques in underdeveloped countries. *Economic Development and Cultural Change*, *7*, 279–285. doi:10.1086/449802

Siebert, S., & Döll, P. (2010). Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *Journal of Hydrology*, *384*, 198–217. doi:10.1016/j.jhydrol.2009.07.031

Smith, B. D. (2011a). General patterns of niche construction and the management of 'wild' plant and animal resources by small-scale pre-industrial societies. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *366*, 836–848. doi:10.1098/rstb.2010.0253

Smith, B. D. (2011b). A cultural niche construction theory of initial domestication. *Biological Theory*, *6*, 260–271. doi:10.1007/s13752-012-0028-4

Steffen, W., Crutzen, P. J., & McNeill, J. R. (2007). The anthropocene: Are humans now overwhelming the great forces of nature. *AMBIO: A Journal of the Human Environment*, *36*, 614–621. doi:10.1579/0044-7447(2007)36[614:TAAHNO]2.0.CO;2

Sterelny, K. (2011). From hominins to humans: How sapiens became behaviourally modern. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *366*, 809–822. doi:10.1098/rstb.2010.0301

Sun, Z., Lorscheid, I., Millington, J. D., Lauf, S., Magliocca, N. R., Groeneveld, J. … Buchmann, C. M. (in press). Simple or complicated agent-based models? A complicated issue. *Environmental Modelling & Software*, *86*, 56–67.

Sutcliffe, A. G., Dunbar, R. I. M., & Wang, D. (2016). Modelling the evolution of social structure. *PLoS One*, *11*(7), e0158605. doi:10.1371/journal.pone.0158605

Tian, G., Kang, B. T., Kolawole, G. O., Idinoba, P., & Salako, F. K. (2005). Long-term effects of fallow systems and lengths on crop production and soil fertility maintenance in West Africa. *Nutrient Cycling in Agroecosystems*, *71*, 139–150. doi:10.1007/s10705-004-1927-y

Tiessen, H., Salcedo, I. H., & Sampaio, E. V. S. B. (1992). Nutrient and soil organic matter dynamics under shifting cultivation in semi-arid northeastern Brazil. *Agriculture, Ecosystems & Environment*, *38*, 139–151. doi:10.1016/0167-8809(92)90139-3

Turchin, P., Currie, T. E., Turner, E. A. L., & Gavrilets, S. (2013). War, space, and the evolution of old world complex societies. *Proceedings of the National Academy of Sciences*, *110*(41), 16384–16389. doi:10.1073/pnas.1308825110

Turner, B. L., II, & Ali, A. (1996). Induced intensification: Agricultural change in Bangladesh with implications for Malthus and Boserup. *Proceedings of the National Academy of Sciences USA*, *93*, 14984–14991. doi:10.1073/pnas.93.25.14984

Tyson, K. C., Roberts, D. H., Clement, C. R., & Garwood, E. A. (1990). Comparison of crop yields and soil conditions during 30 years under annual tillage or grazed pasture. *The Journal of Agricultural Science*, *115*, 29–40. doi:10.1017/S0021859600073883

Valbuena, D., Verburg, P. H., & Bregt, A. K. (2008). A method to define a typology for agent-based analysis in regional land-use research. *Agriculture, Ecosystems & Environment*, *128*(1–2), 27–36. doi:10.1016/j.agee.2008.04.015

Van Vugt, M., Roberts, G., & Hardy, C. (2007). Competitive altruism: Development of reputation-based cooperation in groups. In R. Dunbar & L. Barrett (Eds.), *Handbook of evolutionary psychology* (pp. 531–540). Oxford: Oxford University Press.

Verburg, P. H., Dearing, J. A., Dyke, J. G., Leeuw, S. V. D., Seitzinger, S., Steffen, W., & Syvitski, J. (2015). Methods and approaches to modelling the anthropocene. *Global Environmental Change*. doi:10.1016/j.gloenvcha.2015.08.007

Verburg, P. H., Ellis, E. C., & Letourneau, A. (2011). A global assessment of market accessibility and market influence for global environmental change studies. *Environmental Research Letters*, *6*, 034019. doi:10.1088/1748-9326/6/3/034019

von Thünen, J. H., & Schumacher-Zarchlin, H. (1875). *Der isolirte Staat in Beziehung auf Landwirthschaft und Nationalökonomie*. Wiegant: Hempel & Parey.

Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. *Ecology and Society*, *9*, 5. Retrieved from http://www.ecologyandsociety.org/vol9/iss2/art5/

Waring, T. M., Goff, S. H., & Smaldino, P. E. (2015). Cultural group selection of sustainable institutions (Version 3). CoMSES Computational Model Library. Retrieved from https://www.openabm.org/model/4627/version/3

Waring, T. M., Kline, M. A., Brooks, J. S., Goff, S. H., Gowdy, J., Janssen, M. A., … Jacquet, J. (2015). A multilevel evolutionary framework for sustainability analysis. *Ecology and Society*, *20*(2), 34. doi:10.5751/ES-07634-200234

Waters, C. N., Zalasiewicz, J., Summerhayes, C., Barnosky, A. D., Poirier, C., Gałuszka, A., … Wolfe, A. P. (2016). The anthropocene is functionally and stratigraphically distinct from the Holocene. *Science*, *351*(6269), aad2622. doi:10.1126/science.aad2622

Weinhardt, J. M., & Vancouver, J. B. (2012). Computational models and organizational psychology: Opportunities abound. *Organizational Psychology Review*, *2*(4), 267–292. doi:10.1177/2041386612450455

Wilson, E. O. (1975). *Sociobiology: The new synthesis*. Cambridge, MA: Belknap Press of Harvard University Press.

Zhong, C., Arisona, S. M., Huang, X., Batty, M., & Schmitt, G. (2014). Detecting the dynamics of urban structure through spatial network analysis. *International Journal of Geographical Information Science*, *28*(11), 2178–2199. doi:10.1080/13658816.2014.914521

Zhou, W.-X., Sornette, D., Hill, R. A., & Dunbar, R. I. (2005). Discrete hierarchical organization of social group sizes. *Proceedings of the Royal Society B: Biological Sciences*, *272*(1561), 439–444. doi:10.1098/rspb.2004.2970