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Research

Agent-based modeling of environment-migration linkages: a review

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ABSTRACT. Environmental change can lead to human migration and vice versa. Agent-based models (ABMs) are valuable tools to study these linkages because they can represent individual migration decisions of human actors. Indeed, there is an increasing, yet small, number of ABMs that consider the natural environment in rural migration processes. Therefore, we reviewed 15 ABMs of environment-migration linkages in rural contexts to synthesize the current state of the art. The reviewed ABMs are mostly applied in tropical contexts, serve a wide range of purposes, and cover diverse scales and types of environmental factors, migration processes, and social-ecological feedbacks. We identified potential for future model development with respect to the (1) complexity of environmental influence factors, (2) representation of relevant migration flows, and (3) type of social-ecological couplings. We found that existing models tend to not include fully integrated feedbacks and provide recommendations for the further development of ABMs to contribute to an understanding of the environment-migration-nexus in the future.

Key Words: *agent-based modeling; environmental change; fully integrated feedbacks; migration; review; social-ecological system*

INTRODUCTION

Environmental change puts tremendous pressure on social-ecological systems. This applies in particular to contexts in which humans both depend on natural resources and affect them. Changes in precipitation patterns, including occurrences of droughts, floods, and sea level rise, pose some of the biggest challenges of environmental change for societies. In addition, the pressure on social-ecological systems is potentially exacerbated by demographic and economic dynamics, such as a growing population or changing market prices. One strategy to deal with these challenges is human migration, including rural-to-urban as well as rural-to-rural migration. The latter is of particular importance in developing countries (Bilsborrow 2002, Zimmerer 2004) where an increasing demand for labor during harvest times pulls people to rural areas.

Besides being triggered by environmental change, migration can also have environmental consequences, including deforestation and degradation of natural resources (Bilsborrow 2002, Carr 2009, Lambin and Meyfroidt 2011). For example, in a global-scale study, Neumann-Hermans et al. (2016) found the strongest forest resource degradation in those villages that were characterized by immigration. In addition to the impacts on the destination, the place of origin can experience environmental consequences of out-migration, for example through changes in land use practices such as a lack of maintenance of terraces causing soil erosion (Collins 1986), reduced intensification through population decline (Preston 1998), or remittances impacting the use of forest resources (Hecht et al. 2015). In summary, indications exist that environmental change, combined with a bundle of socioeconomic factors, can lead to migration which, in turn, can trigger additional environmental change (de Sherbinin et al. 2008, Foresight 2011).

There is a growing body of literature on environment-migration linkages based on an emerging number of case studies, and major strides were made with respect to theory development (e.g., Black et al. 2011, McLeman 2013*a*, 2017, Hunter et al. 2015). Still, considerable research gaps exist regarding the interplay of environmental and nonenvironmental migration determinants as well as regarding the social-ecological impacts of environmentally induced migration at both the migrant's destination and the place of origin (Hunter et al. 2015). Overall, there is a lack of understanding on how environmental changes and migration mutually reinforce each other.

Simulation models have the potential to address these gaps (McLeman 2013*b*, Neumann and Hilderink 2015). They can explicitly include feedbacks between the social and the ecological system and enable the simulation of future trajectories under different scenarios. Aggregated modeling approaches include the work of Krol and Bronstert (2007) who simulated linkages between climate change, water availability, agricultural economy, and migration for northeast Brazil. The authors conclude that migration is largely driven by mean municipality income being a function of climate change, water availability, and agricultural yields. In a recent study, Rigaud et al. (2018) integrated the shared socioeconomic pathway (SSP) narratives in a gravity model to estimate flows of people who left their home because of sea level rise, water availability, and crop productivity decline. Modeling results show that by 2050, approximately 140 million people across sub-Saharan Africa, Latin America, and South Asia could be forced to move within their own countries as consequence of climate change.

Together, these studies represent a valuable contribution to the exploration of possible future trajectories of climate induced migration by covering large regions. Yet, they tend to disregard that migration emerges from the complex decision making of heterogeneous individuals and their interactions. It is this importance of individual behavior that brings our attention to agent-based modeling. Agent-based models (ABMs) with their ability to depict how individual decision processes lead to changes at the population level are valuable tools in the discipline of

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demography (Willekens et al. 2017). What is equally important for studying environmentally induced migration is the capability of ABMs to represent social-ecological feedbacks in complex social-ecological systems (Schlüter et al. 2012). This is why ABMs have been widely used to study land use/land cover change (Parker et al. 2003, Matthews et al. 2007, Groeneveld et al. 2017), ecosystem and environmental management (Bousquet and Le Page 2004, Kelly et al. 2013), and various types of mobility and flight (Huang et al. 2014, Hattle et al. 2016, Suleimenova et al. 2017). As such, the capability of including social-ecological feedbacks makes ABMs a valuable tool for exploring the environment-migration nexus, which is reflected by the recently increasing, yet small, number of ABMs that consider the role of the natural environment in rural migration processes[1] (cf. McLeman 2013*b*, Klabunde and Willekens 2016).

Therefore, it is time to systematically review existing ABMs of environment-migration linkages to further advance the development of ABMs in this field. Our research objectives are first, to provide a conceptual framework for social-ecological systems connected by human migration for describing and comparing ABMs. Building upon this framework, we provide a classification for one-way linkages, partly integrated linkages, and fully integrated two-way linkages in the system. Second, we review 15 existing ABMs on rural migration processes to synthesize the current practice in agent-based modeling of environment-migration linkages. In particular, we address the following research questions:

1. Which migration processes have been studied with ABMs, e.g., in- and/or out-migration, return?
2. Which environmental, economic, and social influence factors of migration decisions are considered in existing ABMs and how?
3. How are social and ecological systems coupled in ABMs of environment-migration contexts? In particular, are environmental consequences of migration studied with ABMs?
4. Do conceptual gaps of modeling environment-migration linkages exist, and if so, what are the reasons?

Finally, we provide directions for further ABM development.

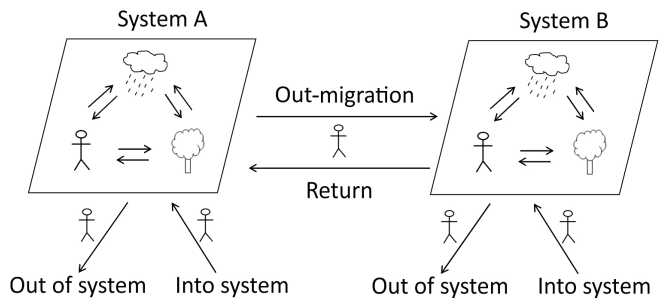
METHODS

Conceptual framework

We developed a conceptual framework of social-ecological systems that are connected through human migration. Here, all possible migration flows, i.e., into, between, and out of the subsystems, as well as the social-ecological interactions within each subsystem are considered (Fig. 1).

The overall system consists of subsystems (A and B). For simplicity reasons we refer to two subsystems; in principle each subsystem can represent more than one origin or destination system. In both subsystems, humans interact with the natural environment. In terms of migration flows, subsystems are characterized by out-migration from subsystem A to subsystem B and/or return-migration from subsystem B to subsystem A. Furthermore, persons can enter subsystems (migration into the system) and/or leave them (migration out of the system). In modeling terms, this process implies that agents are newly initialized or deleted in the course of the simulation. In other words, a person that sends remittances or information to its place of origin does not migrate out of the system but stays within the system.

Fig. 1. Conceptual framework of coupled social-ecological systems connected through migration. Tree and rain cloud represent the natural environment and the stick man represents the human actor; each of the subsystems can represent more than one origin or destination system.



Box 1:

To represent the interactions within the subsystems we adapted Parker et al. (2008) and differentiate between one-way linkages, partly integrated linkages, and fully integrated two-way linkages:

- For one-way linkages, agents are influenced by the environment but do not influence it vice versa.
- In the case of partly integrated linkages, agents make natural resource-use decisions and are in turn influenced by them in their migration decision. For example, agents harvest natural resources in and are influenced in their migration decision via the harvest success. Importantly, the agents' decisions have no lasting impact on the environment; hence, there is no closed-loop feedback between the environmental and the human system.
- Fully integrated two-way linkages imply that environmental consequences of natural resource use and migration decisions are considered within the model, e.g., resource depletion or soil degradation.

The different types of linkages have been included in well-known stylized ABMs of social-ecological systems. Both partly integrated and fully integrated linkages are present in different versions of the Sugarscape model (Epstein and Axtell 1996). In Sugarscape, the landscape comprises cells with various amounts of sugar. In each time step, agents stay put or move to an unoccupied cell and then consume all the sugar available on their current location. In the version with immediate grow back, the sugar completely regrows to its maximum in the next time step, thus forms a partly integrated linkage. A fully integrated two-way linkage is present in gradual grow back because the amount of sugar increases only incrementally in each time step. Thus, agents have an impact on the availability of natural resources of the following time steps. According to our knowledge, no well-known one-way integrated version of Sugarscape exists, but could be imagined in a way that agents are attracted by different amounts of sugar, but do not actually consume it.

The purpose of this framework is to enable us to describe and compare ABMs on environmentally induced migration with regard to the linkages within and between the subsystems. Therefore, our framework is complementary to generic standards for describing ABMs such as the ODD+D framework (Müller et al. 2013). The ODD+D framework addresses modeling choices such as temporal and spatial scales, various model design concepts, and details of human decision making. However, because of this broad scope, the ODD+D framework does not consider specific aspects that need to be addressed in ABMs for environmentally induced migration such as types of migration flows. While focusing on describing and comparing ABMs, our framework does not provide guidelines for model testing and analysis. For this, frameworks such as the TRACE (TRAnsparent and Comprehensive model Evaludation) framework (Schmolke et al. 2010, Grimm et al. 2014) for documenting the development and testing of models represent valuable complements to our framework.

Paper selection

In March 2017, we performed a Web of Science topic search to obtain a systematic and unbiased literature selection. For this purpose, we adapted the search term proposed by Klabunde and Willekens (2016) to include a wide range of synonyms used for the method of ABMs (see Table 1). We did not restrict our search to a certain period of publication.

Table 1. Search terms used for the Web of Science topic search.

	Search terms
Included	
	agent-based model* OR agent-based simulation OR (agent AND based AND model*) OR (multi AND agent); migration
Excluded	
	cancer OR medicine OR tumour OR disease OR therap*; server OR sensor; chemi*OR biolog*OR mineral*OR seismic*

From the resulting 508 articles we extracted those publications describing ABMs in which migration decisions in rural contexts are influenced by at least one environmental factor, e.g., rainfall. We excluded urban-urban migration as well as constantly moving societies including pastoralists, hunter and gatherers. This led to 14 publications.

We complemented this set by considering the non-ISI listed *Journal of Land Use Science*, which is an important outlet for ABMs. This step resulted in one additional publication. Furthermore, we included four relevant papers identified by Klabunde and Willekens (2016) and within our own network. Additionally, we added two non-ISI-listed technical reports as additional references for two of the identified publications because they provided a more detailed model description than the respective ISI-listed publication. Finally, we checked all publications that cited the review of Klabunde and Willekens (2016) and performed a Web of Science topic search using "microsimulation" instead of "agent-based model" and "mobility" and "movement" instead of "migration." Both steps did not result in additional ABMs fulfilling our consideration criteria described above. As a result, 21 publications describing 15 ABMs were considered for this review.

Model categorization

We reviewed the identified 15 ABMs according to the conceptual framework described above and according to the categories listed in Table 2. We developed a standardized protocol for categorizing the models and investigating how rural migration is modeled. Based on the conceptual diagram we additionally drafted diagrams for each ABM to visualize the considered processes; the diagrams for each of the ABMs can be found in the Appendix 1. Each ABM was categorized by two authors of this article and we subsequently sent our results to the developer of the ABM for an additional cross-check. This final step enabled us to eradicate possible misinterpretations; the response rate was 87%.

The following definitions were used for classifying the ABMs:

Context-specific conceptual model: In a context-specific ABM, model processes are based on data or expert knowledge specific to a case study, represented in a stylized model; however, it is not based on a specific geographic region or spatially explicit data (based on Groeneveld et al. 2017).

Migration flows: Systems can be characterized by out-migration from subsystem A to subsystem B and return-migration from subsystem B to subsystem A. In the latter case, agents can move directly back to the origin (direct return) or do so via multiple stops (indirect return). Furthermore, humans can in-migrate from outside the two subsystems into subsystem A and/or B and humans can out-migrate from subsystem A and/or B to somewhere outside the overall system. Migration was only classified as "out of system" for agents that had no opportunity of returning within the model setup and did not interact with their origin system by sending information or remittances.

Duration of migration (seasonal/permanent): We differentiate between seasonal and permanent migration. Seasonal migration is characterized by short-term absence, i.e., less than a year, from the place of origin. In the context of natural resource use, this type of migration is often aligned to harvest cycles. In the case of permanent migration, migrants leave with the intention to stay for long-term periods. However, it is not precluded that they move on or return after a short-term because of changing conditions.

Properties of the destination system known: This indicates whether the agents consider properties of the destination system, e.g., availability of natural resources or market prices in the destination system, in their decision to migrate there.

Direct/indirect environmental influence factors: We assessed whether environmental influence factors are conceptualized as direct, e.g., agents consider amount of precipitation when deciding to migrate or not, or indirect drivers, e.g., rainfall affects income, which agents consider when deciding whether to migrate or not.

Abiotic/biotic: Abiotic are all environmental factors that are not influenced by living organism, e.g., climate, atmosphere, temperature, light. Biotic are all environmental factors that are influenced by living organisms, e.g., plant growth, soil quality.

Social network: Social networks are explicitly modeled social linkages, e.g., through remittance, information exchange, dependents. If agents compare their own situation with that of others or consider the impact a decision has on others, it is not considered a network effect.

Table 2. Categories to classify the reviewed agent-based models. The † marks terms that are explained in the text.

	Category	Response options
General model characteristics	Model purpose	System understanding, prediction (quantitative), management or decision support, communication (participatory approaches), theory development, hypothesis testing, not clearly stated
	Case study	Yes, no, context-specific conceptual model† Indicate the location of case study
	Spatial scale	Indicate the extent and resolution
	Temporal scale	Indicate the extent and resolution
Migration process	Migration flow†	Out-migration, direct return, indirect return, out of system, into system
	Properties of the destination system known†	Yes, no
	Duration†	Seasonal, permanent, both
Environmental influence factors	Influence†	Direct, indirect
	Number of factors	Indicate the total number of factors included
	Which factors	Indicate the factors
	Type†	Abiotic, biotic
Other influence factors	Type	Economic, social, both
	Which factors	Indicate the factors
	Social network†	Yes, no Indicate how networks were modeled
Social-ecological feedbacks	Type of coupling†	One-way linkage, partly integrated, fully integrated
Decision making	Methodology for simulating migration decision†	Probability function, decision theory, heuristics, optimization
	Other decision processes besides migration decision	Cropping, livestock, hunting, others, none
	Others	Indicate which other decision processes are included

Social-ecological feedbacks (one-way linkages/partly integrated linkages/fully integrated two-way linkages): We assessed the models following the classification introduced with our conceptual framework.

Migration decision (probability function/decision theory/heuristics/optimization): We assessed the approach used for simulating a migration decision. A “probability function” can be any function that includes a stochastic factor to determine the migration decision, e.g., random destination, logistic regression function. Models that are based on “decision theory” use an existing decision theory from economics, psychology, or other fields, e.g., Theory of Planned Behavior. “Heuristics” are simple decision rules or rules of thumb, e.g., the if-then rule. “Optimization” includes any form of maximization of a certain indicator, e.g., income, fitness, happiness.

RESULTS AND DISCUSSION

Overview

The number of ABMs that resulted from our literature search is substantially lower than the 27 ABMs reviewed by Klabunde and Willekens (2016) who analyzed migration ABMs in general. This indicates that a substantial share of ABMs in the field of migration does not consider environmental factors.

Table 3 provides an overview of the 15 reviewed models. All considered ABMs are used for gaining system understanding, which is in line with other fields of ABMs (e.g. land use ABMs reviewed by Groeneveld et al. 2017). Four ABMs are used within participatory contexts (e.g. Naivinit et al. 2010, Wu et al. 2011), three to provide decision support (e.g. Smajgl and Bohensky 2013) and three for predicting numbers of migrants (e.g. Berman et al. 2004, Hassani-Mahmooei and Parris 2012).

The temporal scales of the reviewed models range from small, e.g., three years in daily time steps in Naqvi and Rehm (2014), to large, e.g., 10,000 years in yearly time steps in Janssen (2010). Numerous models applied different time steps for simulating different processes and, thereby, tackle the challenge of subsystems operating at different temporal scales as discussed by Martin and Schlüter (2015). For example, Smajgl and Bohensky (2013) use daily time steps for capturing environmental processes and weekly time steps for household-level processes such as migration. In this case, migration processes are modeled with a coarser temporal resolution than the remaining model processes.

The spatial scales cover a wide range from local (e.g., Naivinit et al. 2010) to national extent (e.g., Kniveton et al. 2011). The majority of reviewed ABMs consider a specific case study (Table 3). The locations of the case studies are distributed across the tropics with a focus in Southeast Asia (Fig. 2). This might indicate that environmental factors or natural resources are linked with human migration especially in this climate zone.

Fig. 2. Global distribution of model applications.

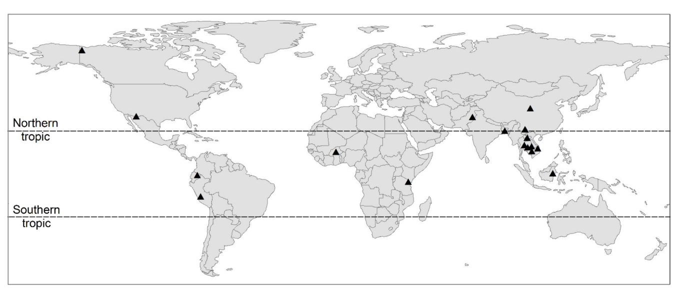
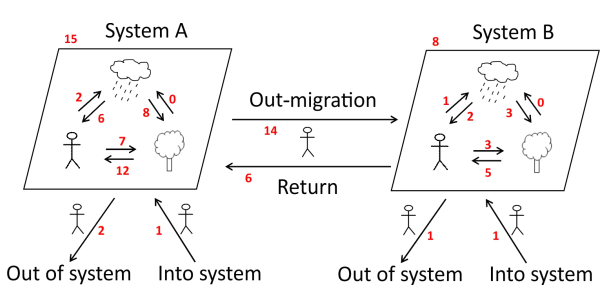


Table 3. Summary of the reviewed agent-based models; the full categorization of each model can be found in the Appendix 1.

Reference(s); model name	Case study	Migration flow	Environmental influence factors (number; type)
Berman et al. 2004	Old Crow, Yukon, Canada	Out-migration, direct return	2; climate warming, caribou numbers
Hadzibeganovic and Xia 2016	None	Out-migration, into system	1; resource availability (food source)
Hassani-Mahmooei and Parris 2012	Bangladesh	Out-migration, indirect return	4 combined in 1; climate shock represented by combination of droughts, floods, cyclones, and sea level rise
Janssen 2010	American Southwest	Out-migration, indirect return	3; rainfall, soil quality depletion and recovery, harvest level
Kniveton et al. 2011, 2012; AMARC	Burkina Faso	Out-migration, direct return	1; rainfall
Magallanes et al. 2014; WankaLab1	Huancayo region, Peru	Out-migration	5; water availability, seasonal rainfall, glacier melt affected by sunlight luminosity and glacier albedo
Mena et al. 2011	Northern Ecuadorian Amazon	Out-migration, direct return	1; slope
Naivinit et al. 2010; BanMakMai model	Ban Mak Mai village, northeast Thailand	Out-migration, direct return	2; rainfall, rice productivity
Naqvi and Rehm 2014; SHELscape	Punjab region, Pakistan	Out-migration, indirect return	2; abstract disaster (interpreted as flooding but not modeled explicitly), food resource availability
Rogers et al. 2011	None	Out-migration, indirect return; out of system	1; resource availability
Smajgl et al. 2009, Smajgl and Bohensky 2013; SimPaSI model	East Kalimantan, Indonesia	Out of system	3; flooding, timber, fish scarcity
Smajgl et al. 2013, Smajgl et al. 2015*a,b*; Mersim model	Mekong region (Laos, Cambodia, Yunnan Province China, Thailand, Vietnam)	Out-migration	5; loss of fish catch, increasing weather variability, water availability, more brackish water, small floods
Smith 2014; RABMM-T	Kilimanjaro Region, Tanzania	Out-migration, direct return	3; rainfall, crop yield, livestock stock
Entwisle et al. 2008, 2016, Walsh et al. 2013	Nang Rong District, northeastern Thailand	Out-migration, direct return	3; rainfall, soil quality and type, crop yield
Wu et al. 2011	China	Out-migration, indirect return	4; agricultural productivity, annual rainfall, annual average temperature, presence of rivers

Figure 3 gives an overview of the framework's elements considered within the reviewed ABMs by counting the occurrences of the framework's elements. Hereby, framework elements are the interlinkages between the environmental factors and the agents, the various migration flows, as well as the origin and destination system.

Fig. 3. Conceptual diagram with the numbers beside the lines indicating the number of agent-based models considering the respective element; the tree represents the availability of natural resources, the rain cloud represents the influencing environmental factors, and the stick man represents the human agent



We grouped the environmental factors considered in the reviewed models (rightmost column in Table 3) into two types: the availability of (1) natural resources, i.e., provisioning services such as resource availability and (2) influencing environmental factors, i.e., mostly factors of environmental change such as rainfall. This distinction is illustrated in the diagram with the tree symbol (natural resources) and the rain cloud symbol (influencing environmental factor). Figure 3 shows that influencing environmental factors determine the availability of natural resources in a large number of models, e.g., soil quality affects crop yields in Janssen (2010). Both natural resources and influencing environmental factors may influence human agents in their decision to migrate. Furthermore, human agents frequently influence the availability of natural resources, e.g., consumption of resources in Hadzibeganovic and Xia (2016)). In contrast, human agents affecting influencing environmental factors is rarely included in the models, e.g., pollution affecting glacier processes in Magallanes et al. (2014).

Types of migration processes

Figure 3 shows that most reviewed ABMs consider out-migration from one subsystem with the option to return in the course of the simulation (e.g., Berman et al. 2004, Rogers et al. 2011). Two ABMs include migration out of the system (Rogers 2011, Smajgl et al. 2013) and one ABM allows for in-migration from outside

Table 4. Environmental factors considered in the reviewed agent-based models.

	Influencing environmental factors (i.e. mostly factors of environmental change)									Availability of natural resources					
	Rainfall	Climate shock (e.g. flood)	Soil quality	Temperature	Glacier characteristics and processes	Increasing weather variability	Sunlight luminosity	Slope	Brackish water	Crop yield	Food resource availability	Water availability	Wildlife availability	Timber	Livestock
Berman et al. 2004				x									x		
Hadzibeganovic and Xia 2016											x				
Hassani-Mahmooei and Parris 2012		x													
Janssen 2010	x		x								x				
Kniveton et al. 2011	x														
Magallanes et al. 2014	x				x		x					x			
Mena et al. 2011								x							
Naivinit et al. 2010	x									x					
Naqvi and Rehm 2014		x									x				
Rogers et al. 2011											x				
Smajgl and Bohensky 2013		x											x	x	
Smajgl et al. 2015*a*		x				x			x			x	x		
Smith 2004	x									x					x
Walsh et al. 2013	x		x							x					
Wu et al. 2011	x			x						x		x			
Sum	7	4	2	1	1	1	1	1	1	4	4	3	3	1	1

the overall system (Hadzibeganovic and Xia 2016). The neglect of migration into and out of the system can be considered a particular strong simplification because, in reality, humans often leave and enter systems such as a country or a region (United Nations 2013). According to our definition, "migration out of system" does not include agents who leave their home and send remittances. Finally, the majority of reviewed ABMs consider permanent migration (see Appendix 1). In contrast, especially in rural areas in the tropics, seasonal migration during the lean season often plays an important role (Henry et al. 2004, Rademacher-Schulz et al. 2014) and there seems to be a lack of ABMs studying this crucial agricultural labor migration.

Factors influencing migration decisions

In eight ABMs, the properties of the destination system, also referred to as pull factors, are influencing the migration decision (indicated at the top left corner of subsystem B in Fig. 3). The number of environmental factors (being push or pull factors, or both) represented per ABM ranges from one to five (Table 3). In most ABMs, environmental factors are considered as indirect drivers (see Appendix 1). This is in line with Black et al. (2011) who conceptualized the indirect role of environmental influence factors in migration processes. In Table 4, we categorize environmental influence factors by the two types "influencing environmental factors" and "availability of natural resources."

Most of the 15 ABMs include both economic and social factors next to environmental factors and a few focus on either economic or social factors next to environmental factors. Four ABMs explicitly model social networks (Berman et al. 2004, Naivinit et al. 2010, Kniveton et al. 2011, Smith 2014). This rather limited representation might partly be due to our strict definition of social networks, but also reflects the complexity associated with modeling social networks. The most frequently considered economic influence factors are distance (to the nearest road, market, or the destination), assets (either on individual, household, or village level, e.g., land, TV, water pump), and income. Among the social influence factors, age, influence by peers (e.g., number of neighbors, fitness of neighbors, behaviors of neighbors, migration of others), gender, population size, migration experience, social ties (e.g., dependent at home), and education are most frequently accounted for. These influence factors are frequently discussed as migration drivers identified in empirical and conceptual studies on environment-migration linkages (e.g., Black et al. 2011, Morrissey 2013, Neumann and Hermans 2017). Interestingly, political influence factors, including discrimination, persecution, conflict, which are known to drive significant migration flows are underrepresented in ABMs, probably because data on how such factors shape individual decisions is scarce.

Coupling of the social-ecological system

We categorized the reviewed ABMs into one-way, partly integrated and fully integrated social-ecological feedbacks (cf. Parker et al. 2008). Table 5 shows the social-ecological feedback included in each of the 15 reviewed ABMs. In five ABMs we found

Table 5. Causal chains representing the social-ecological feedbacks within the reviewed agent-based models (ABM); italic terms represent actions taken by the agents; the term in brackets applies only for parts of the causal chain, i.e., forest economy is affected by timber scarcity.

ABM	Causal chain
One-way linkage	
Berman et al. 2004	Climate warming -> Caribou numbers -> Hunting success -> *Migration decisions*
Hassani-Mahmooei and Parris 2012	Climate shocks -> *Migration decision*
Kniveton et al. 2011	Rainfall -> *Migration decision*
Smith 2004	Rainfall -> Livestock and crop yield -> Income and food production -> *Migration decision*
Wu et al. 2011	Presence of rivers, rainfall and temperature -> Agricultural productivity -> *Migration decision*
Partly integrated	
Mena et al. 2011	Slope -> *Land use selection* -> Assets -> *Migration decision*
Naivinit et al. 2010	Rainfall + *Rice planting* -> Rice growth -> Income -> *Migration decision*
Naqvi and Rehm 2014	Disaster + *Food production* -> Food resource availability -> Income -> *Migration decision*
Walsh et al. 2013	Rainfall, soil quality + *Crop choice* -> Crop yields -> Household assets -> *Migration decisions*
Fully integrated	
Hadzibeganovic and Xia 2016	Resource availability -> Fitness -> *Migration decision* -> Resource availability
Janssen 2010	Soil quality + Rainfall -> Harvest level -> *Migration decision* -> Population density -> Soil quality
Magallanes et al. 2014	Rain, sunlight, albedo, glacier melts -> Water availability -> Comfort level -> *Migration decisions* -> Glacier melt
Rogers et al. 2011	Resource availability -> *Migration decision* -> Resource availability
Smajgl and Bohensky 2013	Flooding, fish scarcity, timber scarcity -> (Forest economy ->) *Migration decisions* -> Fish scarcity, timber scarcity
Smajgl et al. 2015*a*	Weather variability, floods, fish catch, brackish water and water availability -> *Migration decisions* -> Fish catch, brackish water, water availability

one-way linkages, i.e., agents are influenced in their migration decision by the environment but do not influence it in turn. Four models include partly integrated linkages, e.g., agents alter land use and are in turn influenced by harvest success (Mena et al. 2011). Six ABMs implement fully integrated linkages and as such consider environmental change as both a cause and consequence of migration decisions, e.g., soil degradation in Janssen (2010).

Six out of 15 models consider fully integrated linkages; although the representation of these feedbacks between social and ecological systems is a strong advantage of ABMs (e.g., Matthews et al. 2007, Schlüter et al. 2012, Filatova et al. 2013) and is advocated in several scientific fields, such as land use modeling (Parker et al. 2008). Interactions between the social and environmental subsystem can either amplify or weaken a regime shift (Filatova et al. 2016), thus, omitting critical interactions could lead to missing or overemphasizing such regime shifts. Of course, it needs to be acknowledged that the incorporation of fully integrated linkages is not necessary in every case; if the system under study does not depend on social-ecological feedbacks, a one-way or partly integrated model can be sufficient, or even better suited, to answer the posed research questions. The important challenge in this respect is to identify crucial linkages, especially because they might occur across different scales and involve indirect feedbacks (Parker et al. 2008). If in doubt, including linkages in a model would allow modelers to check their importance in a sensitivity analysis.

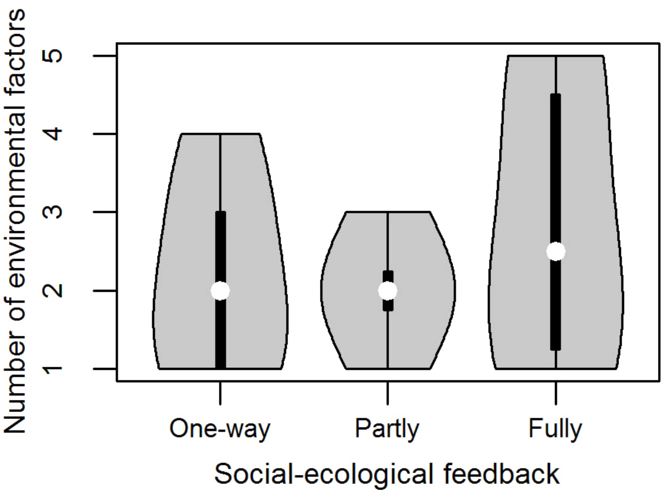
Should fully integrated social-ecological feedbacks be required, implementing them most likely implies increasing the model complexity, possibly leading to reduced transparency (Müller et al. 2014) or difficulties regarding parameterization (Smajgl et al. 2011) and model analysis (Lee et al. 2015). A fully integrated model will be more difficult to understand, to parameterize, and to validate against real world data. This increased difficulty in model development and analysis is also indicated by our result that fully integrated ABMs contain a slightly higher number of environmental factors than one-way or partly integrated models. Yet, this insight is based on a limited number of models and therefore can only be seen as an indication rather than as statistically robust result.

The challenge of matching the conceptual framework

As visualized in Figure 3, some elements of our conceptual framework receive more attention than others. The number of considered framework elements per ABM is on average 6.4 out of the 20 framework elements. Here, we aim to shed light on the reasons for the limited number of framework elements per ABM and discuss how various model parts relate to each other. As such, we are particularly interested in how the representation of social-ecological feedbacks is associated with the number of environmental factors or the representation of migration flows and migration decisions.

The number of environmental factors being included in the reviewed models is slightly higher for ABMs with fully integrated two-way linkages (Fig. 4) than for one-way and partly integrated ABMs. For example, Magallanes et al. (2014) implemented a fully integrated coupling that represents the complex biophysical process of water availability being affected by the interplay of human action and glacier processes (see Table 5). In Janssen (2010), the fully coupled process of humans affecting agricultural harvest levels via soil depletion is reflected in the larger number of environmental variables compared to the number of considered environmental factors in the other reviewed ABMs. In contrast, fully integrated models with low numbers of environmental factors also exist. For example, Rogers et al. (2011) present a fully integrated ABM with only one environmental factor.

Fig. 4. Type of social-ecological coupling and the number of environmental factors included in the agent-based model. The white dot indicates the median; the bold bar indicates the first and the third quartiles.

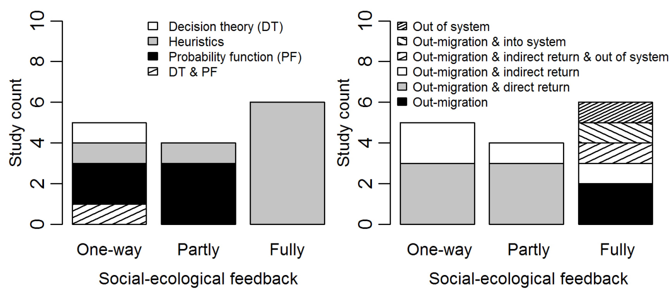


We identified a relationship between the type of coupling and the decision rules used to model migration decisions: decision models based on probability functions or decision theories are exclusively used in ABMs with one-way or partly integrated linkages (Fig. 5). For example, the one-way integrated models by Kniveton et al. (2011) and Smith (2014) use the Theory of Planned Behavior to model migration decisions (Ajzen 1985, 1991). In contrast, all ABMs with fully integrated linkages solely contain heuristics, i.e., simple decision rules or rules of thumb such as if-then rules. For example, in the fully integrated models by Smajgl et al. (2015*a*) and Smajgl and Bohensky (2013) migration decisions are based on Boolean variables, which were derived from interviews and households and indicate whether an agent would migrate in a particular situation, e.g., if fish scarcity exceeds a certain level. This relationship between type of coupling and the representation of migration decisions might hint at the challenges for combining complex decision rules with complex social-ecological feedbacks for model development. Here, the goal to model human decisions in general and migration decisions in particular in a comprehensive way in ABMs seems to challenge considering fully integrated feedbacks. Modeling human decisions to study social-ecological systems is of increasing importance (Groeneveld et al. 2017). Although progress such as the use of decision theories is being made (Schlüter et al. 2017), the flexibility and complexity of human decisions still represent major challenges for modeling.

All reviewed ABMs with one-way or partly integrated linkages consider out-migration together with an either direct or indirect return of migrants (Fig. 5). Yet, migration into or out of the system is solely included in fully integrated two-way integrated ABMs. This indicates that modelers seem to focus either on representing human decision making in as detailed a manner as possible, e.g., by using decision theories, see Groeneveld et al. 2017) or on representing fully integrated social-ecological feedbacks (see Filatova et al. 2013) and considering all possible migration flows.

One reason for this observation might be missing data and understanding of the complex environment-migration context. Bilsborrow and Henry (2012) state that, very seldom does sufficient data on both environmental factors and migration exist from the same region and the same time. The lack of input data has also been identified for ABMs in general (Schulze et al. 2017). For example, data on individual decision making would improve the representation of decision making in ABMs (Filatova et al. 2013). A second reason for the focus on specific model parts are challenges associated with analyzing complex models (Sun et al. 2016). The discussion of difficulties and strategies for analyzing complex ABMs has been gaining more and more attention recently (e.g., Polhill et al. 2016 for systemic change, Filatova et al. 2016 for regime shifts, Lee et al. 2015 and Buchmann et al. 2016 for empirical ABMs).

Fig. 5. Type of social-ecological coupling and the decision rule used to model migration decisions (left) and the migration flow considered within the agent-based model (right).



Methodological considerations

Categorizing ABMs based on provided model descriptions is always prone to subjective biases. To limit such biases and to mitigate possible misinterpretation, we did a cross-check within our author team as well as with the authors of the reviewed models. Advancing the practice of describing models by using standard protocols is a crucial step in tackling the challenge of model communication (e.g., Müller et al. 2013, 2014).

Categorizing ABMs requires the use of consistent definitions. Hence, the conclusions drawn from our review depend on the applied definitions. For example, our strict definition of social networks and of migration out of the system has contributed to the small numbers of ABMs in these categories. Similarly, in order to cover all relevant ABMs we applied a broad definition of environmental factors. For example, we categorized “crop yields” as natural resource, which could also be seen as an economic factor.

Finally, as we focused our review on ABMs of the environment-migration-nexus in rural contexts of natural resource use, we applied a rigorous procedure of eliminating ABMs, including urban-urban migration and residential mobility. This led to a limited number of ABMs to review, which hampers a statistical analysis of the results.

CONCLUSION

In this study, we reviewed 15 ABMs of environment-migration linkages to synthesize the current practice in this field and to further advance the model development. We provide a conceptual framework for social-ecological systems connected through human migration, which can be used for describing and comparing ABMs. In summary, we found that ABMs considering environment-migration linkages are still scarce. Given the importance of environment-migration linkages, we call for further developing ABMs of environment-migration linkages and would like to highlight promising ways forward in advancing this field. This also implies intensifying interdisciplinary work between social and natural scientists, modelers, and empiricists to appropriately depict human decision making in such ABMs and to understand and represent linkages of social and ecological systems.

Most reviewed ABMs represent case studies in the tropics, serve a wide range of model purposes, and cover diverse spatio-temporal scales. Based on our analysis, we identified major gaps with respect to modeling environment-migration linkages. First, important migration flows such as migration into and out of the system as well as temporary migration processes currently receive little attention in ABMs of environment-migration linkages. Furthermore, 9 out of 15 models lack fully integrated social-ecological feedbacks. Exploiting the potential of social-ecological models by implementing more fully coupled systems is essential for exploring whether environmental changes and migration mutually reinforce each other, although drawbacks such as increasing model complexity exist.

To close these gaps, standards for developing and analyzing ABMs are needed. These standards should include the development and realization of strategies for sharing and reusing social-ecological ABMs, the provision of methodological guidelines for analyzing complex social-ecological ABMs such as the TRACE framework (Schmolke et al. 2010, Grimm et al. 2014) and the further propagation of using standard protocols for documenting ABMs such as the ODD+D protocol (Müller et al. 2013). Specifically for the ABM development in the field of environment-migration linkages, we propose our conceptual framework for assisting model development. Together with standards for supporting a good practice of model development, documentation, and analysis, this will help to advance agent-based modeling of environment-migration linkages and thereby foster an understanding of the environment-migration-nexus in the future.

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[1] In the remainder of the article we use the term "rural migration" to refer to rural-rural as well as to rural-urban migration.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/10200

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Sun, Z., I. Lorscheid, J. D. Millington, S. Lauf, N. R. Magliocca, J. Groeneveld, S. Balbi, H. Nolzen, B. Müller, J. Schulze, and C. M. Buchmann. 2016. Simple or complicated agent-based models? A complicated issue. *Environmental Modelling & Software* 86:56-67. http://dx.doi.org/10.1016/j.envsoft.2016.09.006

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Walsh, S. J., G. P. Malanson, B. Entwisle, R. R. Rindfuss, P. J. Mucha, B. W. Heumann, P. M. McDaniel, B. G. Frizzelle, A. M. Verdery, N. E. Williams, X. Yao, and D. Ding. 2013. Design of an agent-based model to examine population—environment interactions in Nang Rong District, Thailand. *Applied Geography* 39:183-198. http://dx.doi.org/10.1016/j.apgeog.2012.12.010

Willekens, F., J. Bijak, A. Klabunde, and A. Prskawetz. 2017. The science of choice: an introduction. *Population Studies* 71 (sup1):1-13. http://dx.doi.org/10.1080/00324728.2017.1376921

Wu, J., R. Mohamed, and Z. Wang. 2011. Agent-based simulation of the spatial evolution of the historical population in China. *Journal of Historical Geography* 37:12-21. http://dx.doi.org/10.1016/j.jhg.2010.03.006

Zimmerer, K. S. 2004. Cultural ecology: placing households in human-environment studies—the cases of tropical forest transitions and agrobiodiversity change. *Progress in Human Geography* 28:795-806. http://dx.doi.org/10.1191/0309132504ph520pr

Appendix 1. Classifications of reviewed models

This document is listed as online resource for the publication:

Title: Agent-based modeling of environment-migration linkages: a review

Journal name: Ecology & Society

This document contains the classifications of the reviewed agent-based models. This includes the diagrams drafted based on the conceptual framework as well as the filled out standardized protocols for each of the reviewed agent-based models.

Berman et al. 2004

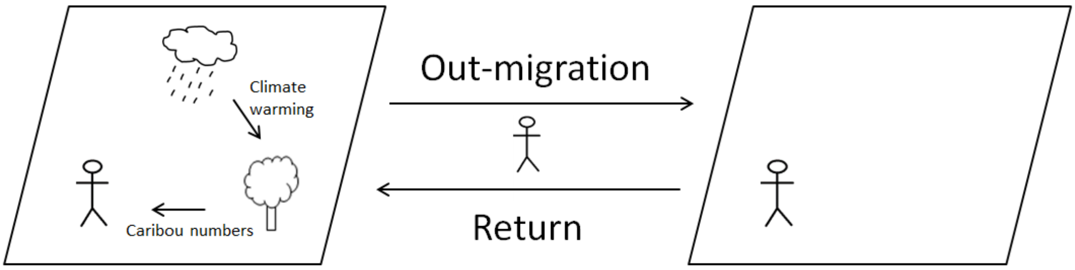

Fig. A1.1 *Diagram drafted for the ABM described by Berman et al. (2004)*

Table A1.1 *Standardized protocol for the ABM described by Berman et al. (2004)*

General
Reference(s): Berman, M., C. Nicolson, G. Kofinas, J. Tetlichi, and S. Martin. 2004. Adaptation and sustainability in a small Arctic community: results of an agent-based simulation model. *Arctic* 57(4):401-414.

Purpose of the study		**Case study**
1. System understanding 2. Prediction (quantitative) 3. Management or decision support 4. Communication (participatory approaches)	5. Theory development 6. Hypothesis testing 7. Not clearly stated *multiple criteria possible*	[Y]es/[N]o/[C]ontext-specific conceptual model (for most of model processes; only hunting and harvesting are based on geographic data) Western Arctic Canadian community of Old Crow, Yukon

Spatial scale	**Temporal scale**
Based on the distance a hunter can travel in one day	40 years with 5 seasons per year (hunting takes place 5 times a year, migration once every 5 years)

Migration process			
Migration flow 1. Out-migration 2. Direct return 3. Indirect return	4. Out of system 5. Into system	**Agents know situation at destination** 1. Yes 2. No	**Duration** 1. Seasonal 2. Permanent 3. Both

Migration decision			
Number of environmental influence factors: 2	**Which factor:** Climate warming, caribou numbers	**Type** 1. Abiotic (climate warming) 2. Biotic (caribou numbers)	**Direct/indirect** 1. Direct 2. Indirect (via hunting success)

<table>
<tr><td>Other influence factors
1. Economic
2. Social
3. Both</td><td>Which factor:
Earnings, household type, age, education, sex</td><td>Social network
1. Yes
2. No</td><td>How:
Sharing of hunting gear and harvest sharing occur throughout the community</td></tr>
<tr><td colspan="4">Methodology
1. Probability function
2. Decision theory
3. Heuristic
4. Optimization</td></tr>
<tr><td colspan="4">Social-ecological feedbacks</td></tr>
<tr><td colspan="4">Type of coupling
1. One-way linkage
2. Partly integrated linkages
3. Fully integrated two-way linkages</td></tr>
<tr><td colspan="4">Other decision processes (besides migration)</td></tr>
<tr><td colspan="2">Object of decision making
1. Cropping
2. Livestock
3. Hunting
4. Other
5. None</td><td colspan="2">Other
Wage employment and hunting</td></tr>
<tr><td colspan="4">Comment: “One-way linkage” is chosen as type of coupling because the ABM does not contain a direct link to caribou population. Caribou numbers are an input to the ABM and are modelled by a caribou population model, which considers total harvest by all communities including the study community.</td></tr>
</table>

Hadzibeganovic & Xia 2016

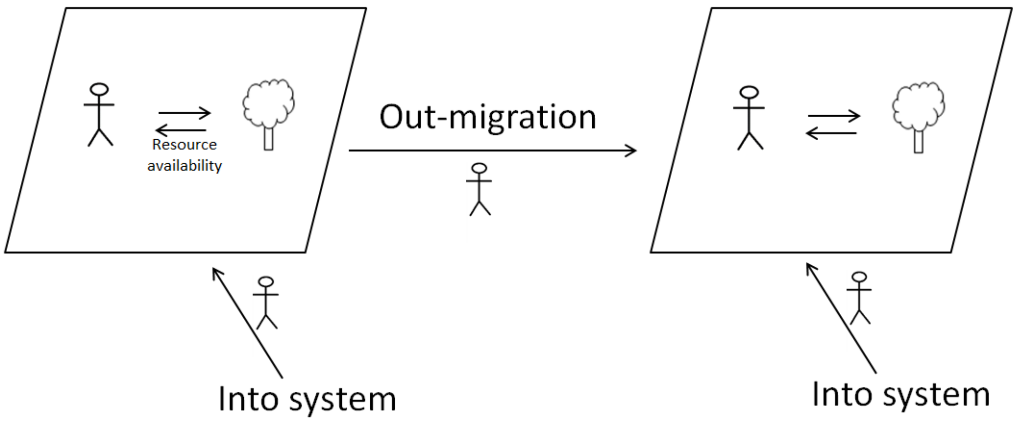

Fig. A1.2 *Diagram drafted for the ABM described by Hadzibeganovic & Xia (2016); the model includes two types of migration decision („reproduction-based" and „payoff-based") of which one is with knowledge of the destination system (i.e. emptiness of a node) and one is not; the case with knowledge of the destination system is illustrated here*

Table A1.2 *Standardized protocol for the ABM described by Hadzibeganovic & Xia (2016)*

General	
Reference(s): Hadzibeganovic, T., and C. Xia. 2016. Cooperation and strategy coexistence in a tag-based multi-agent system with contingent mobility. *Knowledge-Based Systems* 112:1-13.	
Purpose of the study 1. System understanding 2. Prediction (quantitative) 3. Management or decision support 4. Communication (participatory approaches) 5. Theory development 6. Hypothesis testing 7. Not clearly stated *multiple criteria possible*	**Case study** [Y]es/[N]o/[C]ontext-specific conceptual model
Spatial scale System size 10000 nodes	**Temporal scale** Model runs until equilibrium was reached; mostly after 5000 steps

Migration process		
Migration flow 1. Out-migration 2. Direct return 3. Indirect return 4. Out of system 5. Into system	**Agents know situation at destination** 1. Yes 2. No	**Duration** 1. Seasonal 2. Permanent 3. Both

Migration decision

Number of environmental influence factors: 1	**Which factor:** Resource availability (food source)	**Type** 1. Abiotic 2. Biotic	**Direct/indirect** 1. Direct 2. Indirect
Other influence factors 1. Economic 2. Social 3. Both	**Which factor:** Average fitness of neighbors	**Social network** 1. Yes 2. No	**How:**
Methodology 1. Probability function 2. Decision theory 3. Heuristic 4. Optimization			

Social-ecological feedbacks

Type of coupling 1. One-way linkage 2. Partly integrated linkages 3. Fully integrated two-way linkages

Other decision processes (besides migration)

Object of decision making 1. Cropping 2. Livestock 3. Hunting 4. Other 5. None	**Other** Prisoner's dilemma games

Hassani-Mahmooei & Parris 2012

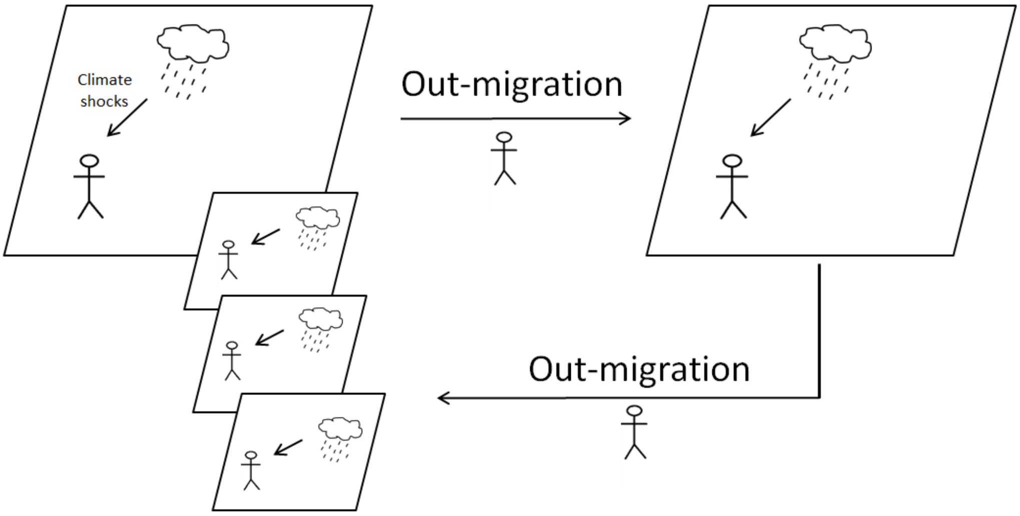

Fig. A1.3 *Diagram drafted for the ABM described by Hassani-Mahmooei & Parris (2012); agents do not make explicit return decisions, but migrate from region to region and can thereby visit a region again at some point in the future*

Table A1.3 *Standardized protocol for the ABM described by Hassani-Mahmooei & Parris (2012)*

<table>
<tr><td colspan="3">General</td></tr>
<tr><td colspan="3">Reference(s):
Hassani-Mahmooei, B., and B. W. Parris. 2012. Climate change and internal migration patterns in Bangladesh: an agent-based model. Environment and Development Economics 17:763-780.</td></tr>
<tr><td colspan="2">Purpose of the study
1. System understanding
2. Prediction (quantitative)
3. Management or decision support
4. Communication (participatory approaches)
5. Theory development
6. Hypothesis testing
7. Not clearly stated
multiple criteria possible</td><td>Case study
[Y]es/[N]o/[C]ontext-specific conceptual model
Bangladesh</td></tr>
<tr><td>Spatial scale
Bangladesh divided in 64 districts</td><td colspan="2">Temporal scale
50 years in monthly time steps</td></tr>
<tr><td colspan="3">Migration process</td></tr>
<tr><td>Migration flow
1. Out-migration
2. Direct return
3. Indirect return
5. Out of system
6. Into system</td><td>Agents know situation at destination
1. Yes
2. No</td><td>Duration
1. Seasonal
2. Permanent
3. Both</td></tr>
</table>

<table>
<tr><td colspan="2"></td><td></td><td></td></tr>
<tr><td colspan="4">Migration decision</td></tr>
<tr><td>Number of environmental influence factors: 4 combined in one</td><td>Which factor:
Climate shock represented by combination of droughts, floods, cyclones and sea level rise</td><td>Type
1. Abiotic
2. Biotic</td><td>Direct/indirect
1. Direct
2. Indirect</td></tr>
<tr><td>Other influence factors
1. Economic
2. Social
3. Both</td><td>Which factor:
Intervening factors: household ownership, land ownership, employment
Pull factors: socioeconomic conditions of the potential destinations (economic variable, education, ethnic composition, infrastructure, health, mutual distance)
Push factors: poverty level, local government development expenditures and unemployment rate</td><td>Social network
1. Yes
2. No</td><td>How:</td></tr>
<tr><td colspan="4">Methodology
1. Probability function
2. Decision theory
3. Heuristic
4. Optimization</td></tr>
<tr><td colspan="4">Social-ecological feedbacks</td></tr>
<tr><td colspan="4">Type of coupling
1. One-way linkage
2. Partly integrated linkages
3. Fully integrated two-way linkages</td></tr>
<tr><td colspan="4">Other decision processes (besides migration)</td></tr>
<tr><td colspan="2">Object of decision making
1. Cropping
2. Livestock
3. Hunting
4. Other
5. None</td><td colspan="2">Other</td></tr>
</table>

Janssen 2010

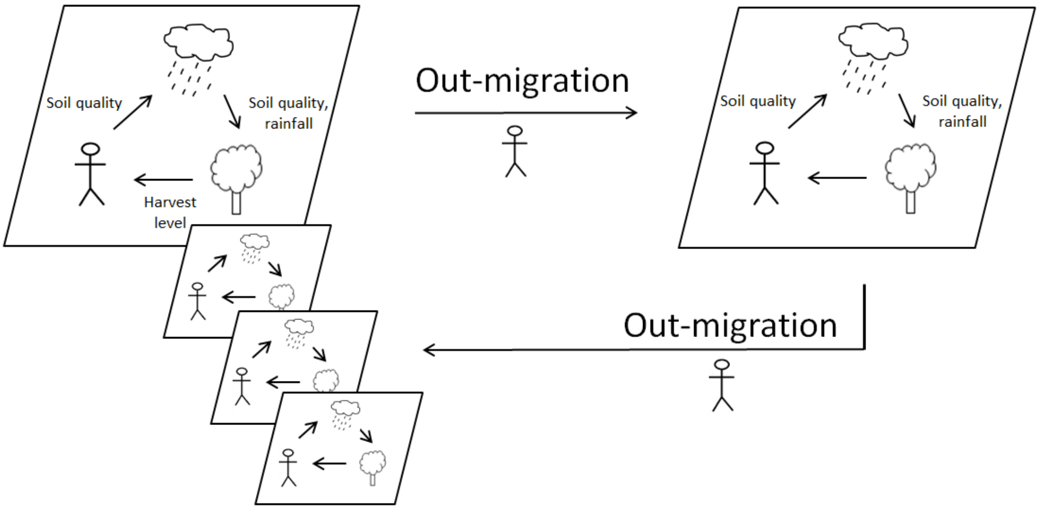

Fig. A1.4 *Diagram drafted for the ABM described by Janssen (2010); agents do not make explicit return decisions, but migrate from region to region and can thereby visit a region again at some point in the future*

Table A1.4 *Standardized protocol for the ABM described by Janssen (2010)*

General		
Reference(s): Janssen, M. A. 2010. Population aggregation in ancient arid environments. *Ecology and Society* 15(2):19.		
Purpose of the study 1. System understanding 2. Prediction (quantitative) 3. Management or decision support 4. Communication (participatory approaches)	5. Theory development 6. Hypothesis testing 7. Not clearly stated *multiple criteria possible*	**Case study** [Y]es/[N]o/[C]ontext-specific conceptual model American Southwest

Spatial scale	**Temporal scale**
20*20 cells with 10*10km	Yearly time steps for 10000 years

Migration process			
Migration flow 1. Out-migration 2. Direct return 3. Indirect return	4. Out of system 5. Into system	**Agents know situation at destination** 1. Yes 2. No	**Duration** 1. Seasonal 2. Permanent 3. Both

Migration decision

Number of environmental influence factors: 3	Which factor: Rainfall, soil quality depletion and recovery, harvest level	Type 1. Abiotic (rain) 2. Biotic (soil quality, harvest)	Direct/indirect 1. Direct (Harvest) 2. Indirect (Soil quality, rainfall)
Other influence factors 1. Economic 2. Social 3. Both	**Which factor:** Population level & experience & required proportion of productivity in current cell (to consider moving costs) & storage	**Social network** 1. Yes 2. No	**How:**

Methodology
1. Probability function
2. Decision theory
3. Heuristic
4. Optimization

Social-ecological feedbacks

Type of coupling
1. One-way linkage
2. Partly integrated linkages
3. Fully integrated two-way linkages

Other decision processes (besides migration)

Object of decision making	Other
1. Cropping 2. Livestock 3. Hunting 4. Other 5. None	Sharing of food and exchange between settlements

Kniveton et al. 2011; Kniveton et al. 2012

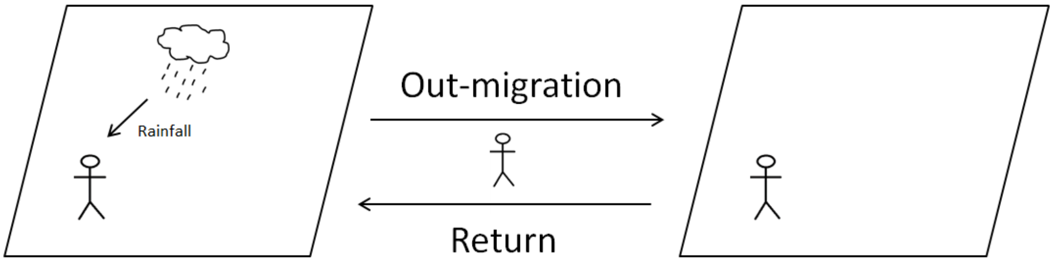

Fig. A1.5 *Diagram drafted for the ABM described by Kniveton et al. (2011; 2012); the destination system is also influenced by rainfall, but as the return decision is not influenced by rainfall it is not depicted visually in the destination system*

Table A1.5 *Standardized protocol for the ABM described by Kniveton et al. (2011; 2012)*

General	
Reference(s): Kniveton, D. R., C. D. Smith, and R. Black. 2012. Emerging migration flows in a changing climate in dryland Africa. *Nature Climate Change* 2:444-447. Kniveton, D. R., C. D. Smith, and S. Wood. 2011. Agent-based model simulations of future changes in migration flows for Burkina Faso. *Global Environmental Change* 21:S34-S40.	
Purpose of the study 1. System understanding 2. Prediction (quantitative) 3. Management or decision support 4. Communication (participatory approaches) 5. Theory development 6. Hypothesis testing 7. Not clearly stated *multiple criteria possible*	**Case study** [Y]es/[N]o/[C]ontext-specific conceptual model Burkina Faso
Spatial scale Burkina Faso divided into 5 regions	**Temporal scale** Validation: 1970 to 2000, scenarios: to 2060. Daily time steps, but birth, ageing, marriage and death events on monthly basis, migration yearly decision

Migration process		
Migration flow 1. Out-migration 2. Direct return 3. Indirect return 5. Out of system 6. Into system	**Agents know situation at destination** 1. Yes 2. No	**Duration** 1. Seasonal 2. Permanent 3. Both

<table>
<tr><td colspan="4">Migration decision</td></tr>
<tr><td>Number of environmental influence factors: 1</td><td>Which factor:
Rainfall</td><td>Type
1. Abiotic
2. Biotic</td><td>Direct/indirect
1. Direct
2. Indirect</td></tr>
<tr><td>Other influence factors
1. Economic
2. Social
3. Both</td><td>Which factor:
age, gender, marital status, assets, experience, behavior of peers</td><td>Social network
1. Yes
2. No</td><td>How:
Fixed network for information exchange; each agent randomly linked to 50 others at initialization</td></tr>
<tr><td colspan="4">Methodology
1. Probability function
2. Decision theory
3. Heuristic
4. Optimization</td></tr>
<tr><td colspan="4">Social-ecological feedbacks</td></tr>
<tr><td colspan="4">Type of coupling
1. One-way linkage
2. Partly integrated linkages
3. Fully integrated two-way linkages</td></tr>
<tr><td colspan="4">Other decision processes (besides migration)</td></tr>
<tr><td colspan="2">Object of decision making
1. Cropping
2. Livestock
3. Hunting
4. Other
5. None</td><td colspan="2">Other</td></tr>
</table>

Magallanes et al. 2014

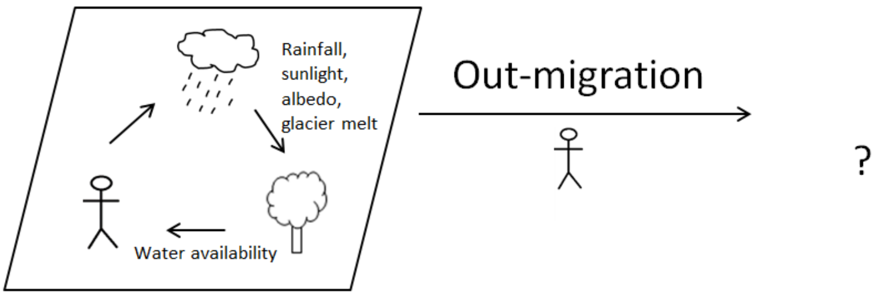

Fig. A1.6 *Diagram drafted for the ABM described by Magallanes et al. (2014)*

Table A1.6 *Standardized protocol for the ABM described by Magallanes et al. (2014)*

General
Reference(s): Magallanes, J. M., A. Burger, and C. Cioffi-Revilla. 2014. Understanding migration induced by climate change in the Central Andes of Peru via agent-based computational modeling. In J. Sichman, E. MacKerrow, F. Squazzoni, and T. Terano, editors. Proceedings of the 5th World Congress on Social Simulation. Sao Paolo, Brazil.

Purpose of the study	**Case study**
1. System understanding 2. Prediction (quantitative) 3. Management or decision support 4. Communication (participatory approaches) 5. Theory development 6. Hypothesis testing 7. Not clearly stated *multiple criteria possible*	[Y]es/[N]o/[C]ontext-specific conceptual model Huancayo region, Peru

Spatial scale	**Temporal scale**
A region covering appox. 400km² subdivided into 5 regions	Monthly time steps, total extent not stated

Migration process		
Migration flow	**Agents know situation at destination**	**Duration**
1. Out-migration 2. Direct return 3. Indirect return 4. Out of system 5. Into system	1. Yes 2. No	1. Seasonal 2. Permanent 3. Both

Migration decision			
Number of environmental influence factors: 5	**Which factor:** Water availability, seasonal rainfall, glacier melt affected by sunlight luminosity and glacier albedo	**Type** 1. Abiotic 2. Biotic	**Direct/indirect** 1. Direct 2. Indirect

Other influence factors 1. Economic 2. Social 3. Both	Which factor: Education, economic level, belonging to a family, success in trading, number of neighbors	Social network 1. Yes 2. No	How:

Methodology
1. Probability function
2. Decision theory
3. Heuristic
4. Optimization

Social-ecological feedbacks

Type of coupling
1. One-way linkage
2. Partly integrated linkages
3. Fully integrated two-way linkages

Other decision processes (besides migration)

Object of decision making 1. Cropping 2. Livestock 3. Hunting 4. Other 5. None	Other

Mena et al. 2011

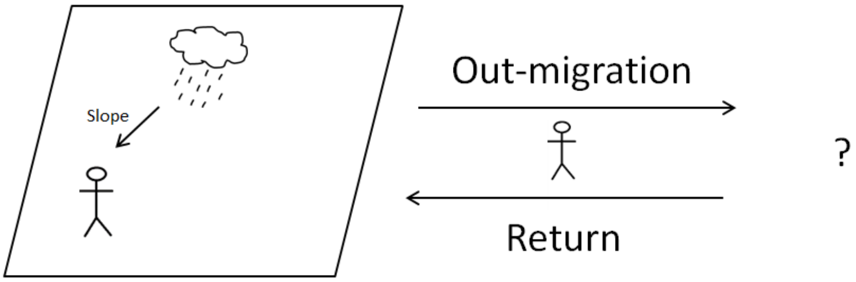

Fig. A1.7 *Diagram drafted for the ABM described by Mena et al. (2011)*

Table A1.7 *Standardized protocol for the ABM described by Mena et al. (2011)*

General
Reference(s): Mena, C. F., S. J. Walsh, B. G. Frizzelle, Y. Xiaozheng, and G. P. Malanson. 2011. Land use change on household farms in the Ecuadorian Amazon: design and implementation of an agent-based model. *Applied Geography* 31(1):210-222.

Purpose of the study		**Case study**
1. System understanding 2. Prediction (quantitative) 3. Management or decision support 4. Communication (participatory approaches)	5. Theory development 6. Hypothesis testing 7. Not clearly stated *multiple criteria possible*	[Y]es/[N]o/[C]ontext-specific conceptual model Northern Ecuadorian Amazon

Spatial scale	**Temporal scale**
approx. 20,000km^2, size of all farms is 50ha	25 years in annual time steps

Migration process			
Migration flow 1. Out-migration 2. Direct return 3. Indirect return	4. Out of system 5. Into system	**Agents know situation at destination** 1. Yes 2. No	**Duration** 1. Seasonal 2. Permanent 3. Both

Migration decision			
Number of environmental influence factors: 1	**Which factor:** Slope	**Type** 1. Abiotic 2. Biotic	**Direct/indirect** 1. Direct 2. Indirect

Other influence factors 1. Economic 2. Social 3. Both	Which factor: Assets (influenced by market prices & maintenance costs), age; gender; number of persons in household; engagement in farm work; household's head education; number of previous out-migrants in the household; population density at the farm; walking distance to the nearest road; distance to nearest market; land use change in crops, pasture and forest from 1990 to 1999	Social network 1. Yes 2. No	How:
Methodology 1. Probability function 2. Decision theory 3. Heuristic 4. Optimization			
Social-ecological feedbacks			
Type of coupling 1. One-way linkage 2. Partly integrated linkages 3. Fully integrated two-way linkages			
Other decision processes (besides migration)			
Object of decision making 1. Cropping 2. Livestock 3. Hunting 4. Other 5. None		**Other**	

Naivinit et al. 2010

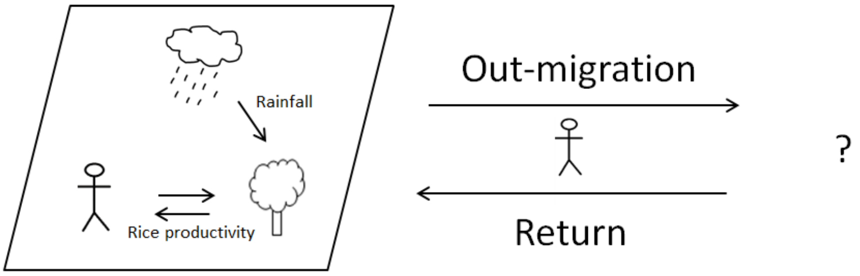

Fig. A1.8 *Diagram drafted for the ABM described by Naivinit et al. (2010)*

Table A1.8 *Standardized protocol for the ABM described by Naivinit et al. (2010)*

General			
Reference(s): Naivinit, W., C. Le Page, G. Trébuil, and N. Gajaseni. 2010. Participatory agent-based modeling and simulation of rice production and labor migrations in northeast Thailand. *Environmental Modelling & Software* 25(11):1345-1358.			
Purpose of the study 1. System understanding 2. Prediction (quantitative) 3. Management or decision support 4. Communication (participatory approaches) 5. Theory development 6. Hypothesis testing 7. Not clearly stated *multiple criteria possible*		**Case study** [Y]es/[N]o/[C]ontext-specific conceptual model Ban Mak Mai village, Northeast Thailand	
Spatial scale Local (one village); 4 households (2*3.6ha and 2*7ha); resolution 0.04ha; abstract landscape setting		**Temporal scale** 10 years; daily time steps; migration decision only once a year	
Migration process			
Migration flow 1. Out-migration 2. Direct return 3. Indirect return 4. Out of system 5. Into system		**Agents know situation at destination** 1. Yes 2. No	**Duration** 1. Seasonal 2. Permanent 3. Both
Migration decision			
Number of environmental influence factors: 2	**Which factor:** Rainfall, Rice productivity	**Type** 1. Abiotic (rain) 2. Biotic (rice productivity)	**Direct/indirect** 1. Direct 2. Indirect

Other influence factors 1. Economic 2. Social 3. Both	**Which factor:** Age, gender, marital status, migration experience, income at household level, dependent at home	**Social network** 1. Yes 2. No	**How:** Individuals belong to households; dependents in household influence migration decisions
Methodology 1. Probability function 2. Decision theory 3. Heuristic 4. Optimization			
Social-ecological feedbacks			
Type of coupling 1. One-way linkage 2. Partly integrated linkages 3. Fully integrated two-way linkages			
Other decision processes (besides migration)			
Object of decision making 1. Cropping 2. Livestock 3. Hunting 4. Other 5. None		**Other**	

Naqvi & Rehm 2014

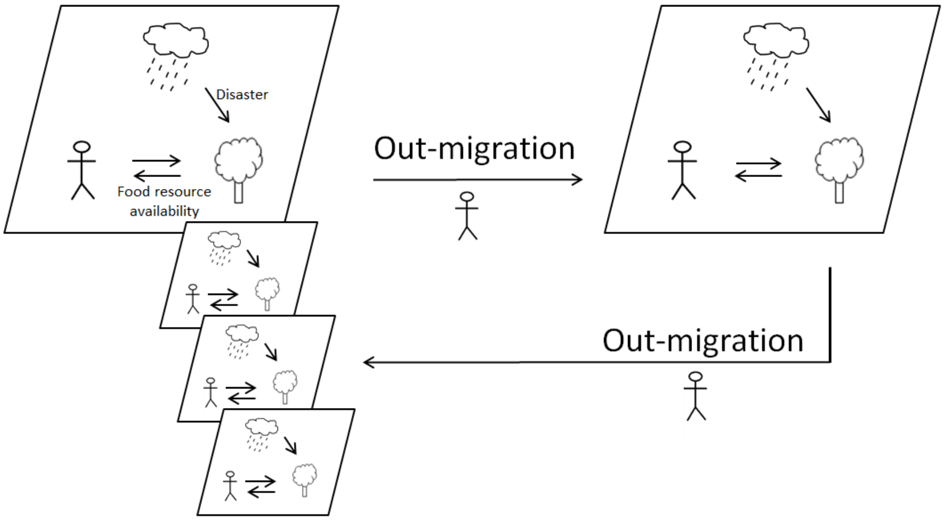

Fig. A1.9 *Diagram drafted for the ABM described by Naqvi & Rehm (2014); agents do not make explicit return decisions, but migrate from region to region and can thereby visit a region again at some point in the future*

Table A1.9 *Standardized protocol for the ABM described by Naqvi & Rehm (2014)*

General
Reference(s): Naqvi, A. A., and M. Rehm. 2014. A multi-agent model of a low income economy: simulating the distributional effects of natural disasters. *Journal of Economic Interaction and Coordination* 9(2):275-309.

Purpose of the study		**Case study**
1. System understanding 2. Prediction (quantitative) 3. Management or decision support 4. Communication (participatory approaches)	5. Theory development 6. Hypothesis testing 7. Not clearly stated *multiple criteria possible*	[Y]es/[N]o/[C]ontext-specific conceptual model Punjab region in rural Pakistan

Spatial scale	**Temporal scale**
9 villages and 3 cities linked through a road network	1 time step is 1 day, simulation results are presented for 3 years in total

Migration process

Migration flow		**Agents know situation at destination**	**Duration**
1. Out-migration 2. Direct return 3. Indirect return	4. Out of system 5. Into system	1. Yes 2. No	1. Seasonal 2. Permanent 3. Both

Migration decision

Number of environmental influence factors: 2	**Which factor:** abstract disaster interpreted as flooding, but not modeled explicitly, food resource availability	**Type** 1. Abiotic (disaster) 2. Biotic (food production)	**Direct/indirect** 1. Direct 2. Indirect
Other influence factors 1. Economic 2. Social 3. Both	**Which factor:** Distance, income	**Social network** 1. Yes 2. No	**How:**

Methodology
1. Probability function
2. Decision theory
3. Heuristic
4. Optimization

Social-ecological feedbacks

Type of coupling
1. One-way linkage
2. Partly integrated linkages
3. Fully integrated two-way linkages

Other decision processes (besides migration)

Object of decision making	**Other**
1. Cropping 2. Livestock 3. Hunting 4. Other 5. None	Related to economic interactions (hiring workers, selling and buying goods)

Rogers et al. 2011

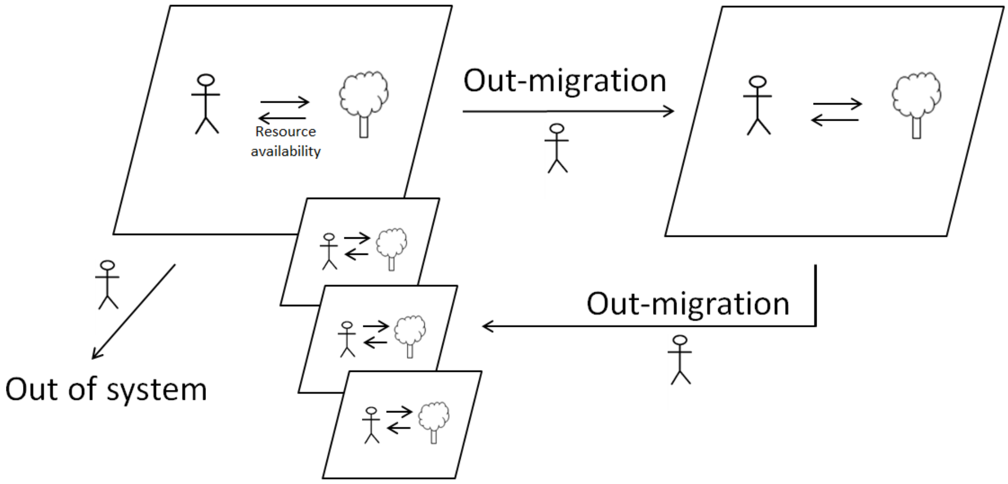

Fig. A1.10 *Diagram drafted for the ABM described by Rogers et al. (2011); agents do not make explicit return decisions, but migrate from region to region and can thereby visit a region again at some point in the future; migration out of the system is possible from all subsystems, but for simplicity reasons it is only visualized for the origin system; the situation in the destination system does not influence the migration decision, but as agents interact with the environment in all visited systems these factors are visualized*

Table A1.10 *Standardized protocol for the ABM described by Rogers et al. (2011)*

General	
Reference(s): Rogers, D. S., O. Deshpande, and M. W. Feldman. 2011. The spread of inequality. *PLoS ONE* 6(9):e24683.	
Purpose of the study 1. System understanding 2. Prediction (quantitative) 3. Management or decision support 4. Communication (participatory approaches) 5. Theory development 6. Hypothesis testing 7. Not clearly stated *multiple criteria possible*	**Case study** [Y]es/[N]o/[C]ontext-specific conceptual model

Spatial scale	Temporal scale
100 sites with same size	Yearly time steps for 2000 years

Migration process

Migration flow	Agents know situation at destination	Duration
1. Out-migration 2. Direct return 3. Indirect return 4. Out of system 5. Into system	1. Yes 2. No	1. Seasonal 2. Permanent 3. Both

Migration decision

Number of environmental influence factors: 1	**Which factor:** Resource availability	**Type** 1. Abiotic 2. Biotic	**Direct/indirect** 1. Direct 2. Indirect
Other influence factors 1. Economic 2. Social 3. Both	**Which factor:** Population decline	**Social network** 1. Yes 2. No	**How:**

Methodology

1. Probability function
2. Decision theory
3. Heuristic
4. Optimization

Social-ecological feedbacks

Type of coupling

1. One-way linkage
2. Partly integrated linkages
3. Fully integrated two-way linkages

Other decision processes (besides migration)

Object of decision making	Other
1. Cropping 2. Livestock 3. Hunting 4. Other 5. None	

Smajgl & Bohensky 2013; Smajgl et al. 2009

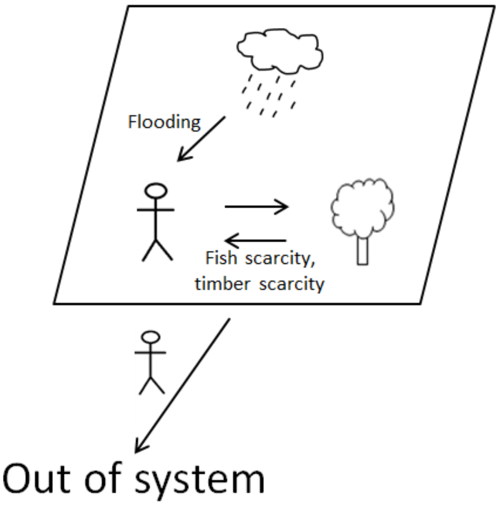

Fig. A1.11 *Diagram drafted for the ABM described by Smajgl & Bohensky (2013) and Smajgl et al. (2009)*

Table A1.11 *Standardized protocol for the ABM described by Smajgl & Bohensky (2013) and Smajgl et al. (2009)*

<table>
<tr><td colspan="2">General</td></tr>
<tr><td colspan="2">Reference(s):
Smajgl, A., and E. Bohensky. 2013. Behaviour and space in agent-based modelling: poverty patterns in East Kalimantan, Indonesia. Environmental Modelling & Software 45:8-14.
Smajgl, A., G. Carlin, A. House, J. Butler, E. Bohensky, A. S. Kurnia, C. Sugiyanto, and M. Hodgen. 2009. Design document for agent-based model SimPaSI Jawa Tengah. Simulating pathways to sustainability in Indonesia. CSIRO, Townsville, Australia.</td></tr>
<tr><td>Purpose of the study
1. System understanding
2. Prediction (quantitative)
3. Management or decision support
4. Communication (participatory approaches)
5. Theory development
6. Hypothesis testing
7. Not clearly stated
multiple criteria possible</td><td>Case study
[Y]es/[N]o/[C]ontext-specific conceptual model
East Kalimantan, Indonesia</td></tr>
<tr><td>Spatial scale
study area consists of six southern districts of</td><td>Temporal scale
Combination of daily (environment) and weekly</td></tr>
</table>

East Kalimantan (approx. 220.400km²)		(households) time steps, 2006 to 2013	
Migration process			
Migration flow 1. Out-migration 2. Direct return 3. Indirect return	4. Out of system 5. Into system	**Agents know situation at destination** 1. Yes 2. No	**Duration** 1. Seasonal 2. Permanent 3. Both
Migration decision			
Number of environmental influence factors: 3	**Which factor:** Flooding, timber, fish scarcity	**Type** 1. Abiotic (flooding) 2. Biotic (fish scarcity and timber)	**Direct/indirect** 1. Direct 2. Indirect (timber affects forest economy)
Other influence factors 1. Economic 2. Social 3. Both	**Which factor:** Fuel price, groundwater price, electricity price, kerosene price	**Social network** 1. Yes 2. No	**How:**
Methodology 1. Probability function 2. Decision theory 3. Heuristic 4. Optimization			
Social-ecological feedbacks			
Type of coupling 1. One-way linkage 2. Partly integrated linkages 3. Fully integrated two-way linkages			
Other decision processes (besides migration)			
Object of decision making 1. Cropping 2. Livestock 3. Hunting 4. Other 5. None		**Other** use of different natural resources (fish, timber)	

Smajgl et al. 2013; Smajgl et al. 2015a; Smajgl et al. 2015b

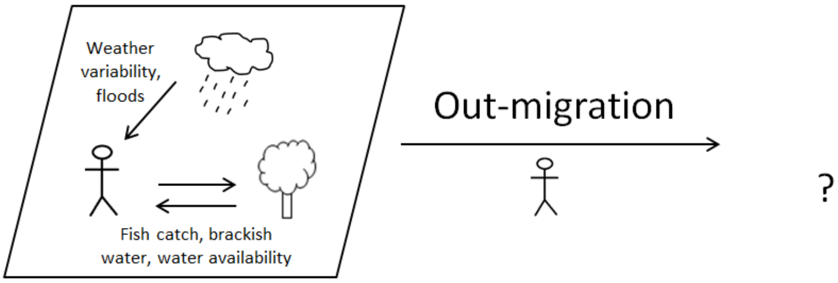

Fig. A1.12 *Diagram drafted for the ABM described by Smajgl et al. (2013; 2015a; 2015b)*

Table A1.12 *Standardized protocol for the ABM described by Smajgl et al. (2013; 2015a; 2015b)*

General		
Reference(s): Smajgl, A., S. Egan, M. Kirby, M. Mainuddin, J. Ward, and F. Kroon. 2013. *The Mekong Region simulation (Mersim) model - design document*. CSIRO Climate Adaptation Flagship, Townsville, Australia. Smajgl, A., J. Xu, S. Egan, Z.-F. Yi, J. Ward, and Y. Su. 2015*a*. Assessing the effectiveness of payments for ecosystem services for diversifying rubber in Yunnan, China. *Environmental Modelling & Software* 69:187-195. Smajgl, A., J. R. Ward, T. Foran, J. Dore, and S. Larson. 2015*b*. Visions, beliefs, and transformation: exploring cross-sector and transboundary dynamics in the wider Mekong region. *Ecology and Society* 20(2):15.		
Purpose of the study 1. System understanding 2. Prediction (quantitative) 3. Management or decision support 4. Communication (participatory approaches)	5. Theory development 6. Hypothesis testing 7. Not clearly stated *multiple criteria possible*	**Case study** [Y]es/[N]o/[C]ontext-specific conceptual model Mekong region (Laos, Cambodia, Yunnan Province China, Thailand, Vietnam)
Spatial scale Extent: Greater Mekong Subregion Resolution: Irregular polygons derived from overlapping various GIS layers (incl. elevation and land cover).	**Temporal scale** Daily time steps; scenarios up to 2029	

Migration process

Migration flow		Agents know situation at destination	Duration
1. Out-migration 2. Direct return 3. Indirect return	4. Out of system 5. Into system	1. Yes 2. No	1. Seasonal 2. Permanent 3. Both

Migration decision

Number of environmental influence factors: 5	Which factor: Loss of fish catch, increasing weather variability, water availability, more brackish water, small floods	Type 1. Abiotic (weather variability, water availability, floods) 2. Biotic (fish catch, brackish water)	Direct/indirect 1. Direct 2. Indirect
Other influence factors 1. Economic 2. Social 3. Both	Which factor: Income changes, industry employment conditions, market access, irrigation scheme, competition among water users, rubber tree replacement	Social network 1. Yes 2. No	How:

Methodology
1. Probability function
2. Decision theory
3. Heuristic
4. Optimization

Social-ecological feedbacks

Type of coupling
1. One-way linkage
2. Partly integrated linkages
3. Fully integrated two-way linkages

Other decision processes (besides migration)

Object of decision making	Other
1. Cropping 2. Livestock 3. Hunting 4. Other 5. None	Use of different natural resources (fish, timber), get income from livelihood activities, modify livelihood as form of adaptation

Smith 2014

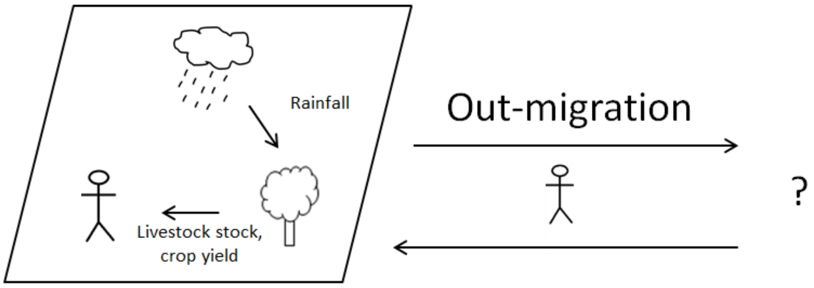

Fig. A1.13 *Diagram drafted for the ABM described by Smith (2014); migrants send remittances back to their household and are therefore not deleted from the system (i.e. this is not „migration out of the system")*

Table A1.13 *Standardized protocol for the ABM described by Smith (2014)*

General		
Reference(s): Smith, C. D. 2014. Modelling migration futures: development and testing of the rainfalls agent-based migration model - Tanzania. *Climate and Development* 6(1):77-91.		
Purpose of the study 1. System understanding 2. Prediction (quantitative) 3. Management or decision support 4. Communication (participatory approaches) 5. Theory development 6. Hypothesis testing 7. Not clearly stated *multiple criteria possible*		**Case study** [Y]es/[N]o/[C]ontext-specific conceptual model Kilimanjaro Region, Tanzania
Spatial scale 3 villages as 3 entities, not spatially explicit	**Temporal scale** Simulation runs from 2015 to 2050, rainfall monthly time steps, human decisions also monthly	
Migration process		
Migration flow 1. Out-migration 2. Direct return 3. Indirect return 4. Out of system 5. Into system	**Agents know situation at destination** 1. Yes 2. No	**Duration** 1. Seasonal 2. Permanent 3. Both (up to 72 months)

Migration decision			
Number of environmental influence factors: 3	**Which factor:** Rainfall, crop yield, livestock stock	**Type** 1. Abiotic (rainfall) 2. Biotic (crop yield, livestock stock)	**Direct/indirect** 1. Direct 2. Indirect
Other influence factors 1. Economic 2. Social 3. Both	**Which factor:** individuals (individual propensity of migration): influence of peers (proportion of peers who have already migrated), age, gender, home village households (actual decision how many household members should migrate): income (dependent on rainfall), number of household members	**Social network** 1. Yes 2. No	**How:** Households are randomly linked to create a network, different scenarios with different numbers of links per household; migration experience of others is influencing own migration decision
Methodology 1. Probability function 2. Decision theory 3. Heuristic 4. Optimization			
Social-ecological feedbacks			
Type of coupling 1. One-way linkage 2. Partly integrated linkages 3. Fully integrated two-way linkages			
Other decision processes (besides migration)			
Object of decision making 1. Cropping 2. Livestock 3. Hunting 4. Other 5. None		**Other**	

Walsh et al. 2013; Entwisle et al. 2008; Entwisle et al. 2016

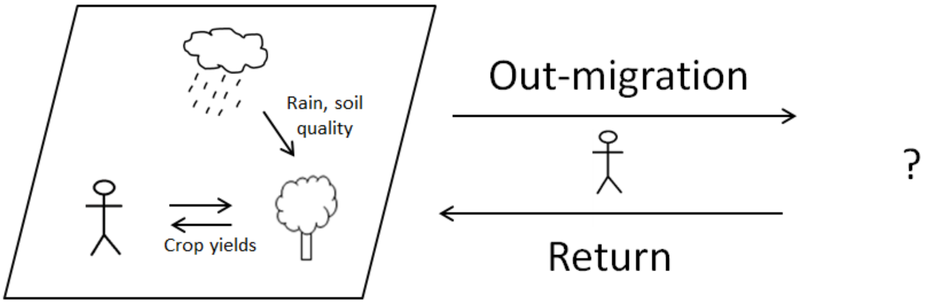

Fig. A1.14 *Diagram drafted for the ABM described by Walsh et al. (2013) and Entwisle et al. (2008; 2016)*

Table A1.14 *Standardized protocol for the ABM described by Walsh et al. (2013) and Entwisle et al. (2008; 2016)*

General		
Reference(s): Walsh, S. J., G. P. Malanson, B. Entwisle, R. R. Rindfuss, P. J. Mucha, B. W. Heumann, P. M. McDaniel, B. G. Frizzelle, A. M. Verdery, N. E. Williams, X. Yao, and D. Ding. 2013. Design of an agent-based model to examine population—environment interactions in Nang Rong District, Thailand. Applied Geography 39:183-198. Entwisle, B., G. Malanson, R. R. Rindfuss, and S. Walsh. 2008. An agent-based model of household dynamics and land use change. Journal of Land Use Science 3(1):73-93. Entwisle, B., N. E. Williams, A. M. Verdery, R. R. Rindfuss, S. J. Walsh, G. P. Malanson, P. J. Mucha, B. G. Frizzelle, P. M. McDaniel, X. Yao, B. W. Heumann, P. Prasartkul, Y. Sawangdee, and A. Jampaklay. 2016. Climate shocks and migration: an agent-based modeling approach. Population and Environment 38:47-71.		
Purpose of the study 1. System understanding 2. Prediction (quantitative) 3. Management or decision support 4. Communication (participatory approaches)	5. Theory development 6. Hypothesis testing 7. Not clearly stated *multiple criteria possible*	**Case study** [Y]es/[N]o/[C]ontext-specific conceptual model Nang Rong District, Northeastern Thailand
Spatial scale 1300km^2, 41 villages, 5m spatial resolution	**Temporal scale** Annual time steps for 25 years	
Migration process		
Migration flow 1. Out-migration 4. Out of system	**Agents know situation at destination**	**Duration** 1. Seasonal

2. Direct return 3. Indirect return	5. Into system	1. Yes 2. No	2. Permanent 3. Both
Migration decision			
Number of environmental influence factors: 3	**Which factor:** Rainfall, soil quality & type, crop yields	**Type** 1. Abiotic (rainfall) 2. Biotic (soil quality, crop yields)	**Direct/indirect** 1. Direct 2. Indirect
Other influence factors 1. Economic 2. Social 3. Both	**Which factor:** Age, population, connectivity of village, migration prevalence, ties to migrants and residents, marital status, percent village has pump, percent village has vehicle, percent village grows cassava, household centrality, gender, kinship dependency, distance to nearest village, percent village has TV, land deed	**Social network** 1. Yes 2. No	**How:** Households are connected in a social network; ties to current migrants, remittances, household centrality, migration prevalence, village connectivity, ties to wealthy households
Methodology 1. Probability function 2. Decision theory 3. Heuristic 4. Optimization			
Social-ecological feedbacks			
Type of coupling 1. One-way linkage 2. Partly integrated linkages 3. Fully integrated two-way linkages			
Other decision processes (besides migration)			
Object of decision making 1. Cropping (land use and fertilizer input) 2. Livestock 3. Hunting 4. Other 5. None		**Other**	

Wu et al. 2011

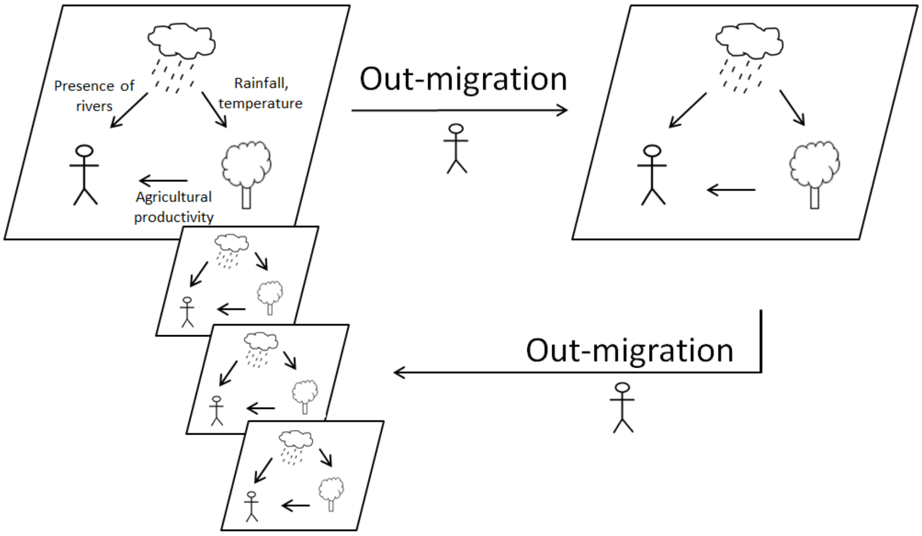

Fig. A1.15 *Diagram drafted for the ABM described by Wu et al. (2011); agents do not make explicit return decisions, but migrate from region to region and can thereby visit a region again at some point in the future*

Table A1.15 *Standardized protocol for the ABM described by Wu et al. (2011)*

<table>
<tr><td colspan="3">General</td></tr>
<tr><td colspan="3">Reference(s):
Wu, J., R. Mohamed, and Z. Wang. 2011. Agent-based simulation of the spatial evolution of the historical population in China. Journal of Historical Geography 37:12-21.</td></tr>
<tr><td colspan="2">Purpose of the study
1. System understanding
2. Prediction (quantitative)
3. Management or decision support
4. Communication (participatory approaches)
5. Theory development
6. Hypothesis testing
7. Not clearly stated
multiple criteria possible</td><td>Case study
[Y]es/[N]o/[C]ontext-specific conceptual model
China</td></tr>
<tr><td>Spatial scale
227*297 cells a 468km^2</td><td colspan="2">Temporal scale
2000 years</td></tr>
</table>

Migration process

Migration flow		Agents know situation at destination	Duration
1. Out-migration 2. Direct return 3. Indirect return	4. Out of system 5. Into system	1. Yes 2. No	1. Seasonal 2. Permanent 3. Both

Migration decision

Number of environmental influence factors: 4	**Which factor:** agricultural productivity, annual rainfall, annual average temperature, presence of rivers	**Type** 1. Abiotic (rainfall, temperature, river) 2. Biotic (agricultural productivity)	**Direct/indirect** 1. Direct (agricultural productivity, rivers) 2. Indirect (rainfall, temperature)
Other influence factors 1. Economic 2. Social 3. Both	**Which factor:** Social: Migration rates, existing settlements, population size Accessibility: distance between provinces	**Social network** 1. Yes 2. No	**How:**

Methodology
1. Probability function
2. Decision theory
3. Heuristic
4. Optimization

Social-ecological feedbacks

Type of coupling
1. One-way linkage
2. Partly integrated linkages
3. Fully integrated two-way linkages

Other decision processes (besides migration)

Object of decision making	Other
1. Cropping 2. Livestock 3. Hunting 4. Other 5. None	

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Smajgl, A., G. Carlin, A. House, J. Butler, E. Bohensky, A. S. Kurnia, C. Sugiyanto, and M. Hodgen. 2009. *Design document for agent-based model SimPaSI Jawa Tengah. Simulating pathways to sustainability in Indonesia*. CSIRO, Townsville, Australia.

Smajgl, A., S. Egan, M. Kirby, M. Mainuddin, J. Ward, and F. Kroon. 2013. *The Mekong Region simulation (Mersim) model - design document.* CSIRO Climate Adaptation Flagship, Townsville, Australia.

Smajgl, A., J. Xu, S. Egan, Z.-F. Yi, J. Ward, and Y. Su. 2015*a*. Assessing the effectiveness of payments for ecosystem services for diversifying rubber in Yunnan, China. *Environmental Modelling & Software* 69:187-195. http://dx.doi.org/10.1016/j.envsoft.2015.03.014

Smajgl, A., J. R. Ward, T. Foran, J. Dore, and S. Larson. 2015*b*. Visions, beliefs, and transformation: exploring cross-sector and transboundary dynamics in the wider Mekong region. *Ecology and Society* 20(2):15. http://dx.doi.org/10.5751/ES-07421-200215

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Walsh, S. J., G. P. Malanson, B. Entwisle, R. R. Rindfuss, P. J. Mucha, B. W. Heumann, P. M. McDaniel, B. G. Frizzelle, A. M. Verdery, N. E. Williams, X. Yao, and D. Ding. 2013. Design of an agent-based model to examine population—environment interactions in Nang Rong District, Thailand. Applied Geography 39:183-198. http://dx.doi.org/10.1016/j.apgeog.2012.12.010

Wu, J., R. Mohamed, and Z. Wang. 2011. Agent-based simulation of the spatial evolution of the historical population in China. Journal of Historical Geography 37:12-21. http://dx.doi.org/10.1016/j.jhg.2010.03.006