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Rural migration under climate and land systems change

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Jonathan Salerno[1,2], Andrea E. Gaughan[3], Rekha Warrier[1], Randall Boone[4], Forrest R. Stevens[3], Patrick W. Keys[5], Lazaro Johana Mangewa[6], Felister Michael Mombo[7], Alex de Sherbinin[8], Joel Hartter[9] & Lori Hunter[10]

Human migration is both a consequence and a cause of environmental change. Related scientific and policy discourse focuses largely on international and urban migration, while rural migration receives far less attention. This is despite rural mobility being a key adaptive strategy for smallholders globally in the face of climate, environmental and social change. The integration of migration studies and land system science may serve to advance understanding of rural migration processes, and in turn advance the science of the fields themselves. Such efforts are relevant in an increasingly mobile world where new models and theory will be needed to meaningfully understand migration dynamics within sustainable socio-environmental systems.

Human migration is often seen as a challenge in the wake of environmental and political crises[1]. Striking examples include displaced residents fleeing New Orleans following Hurricane Katrina and then slowly returning, refugees escaping conflict and poverty from the Middle East and Africa arriving on European coastlines, and families in camps or detention centres on the southern border of the United States. Although refugee scenarios capture broad public attention[2], most migration events are adaptive as opposed to disaster- or conflict-induced and occur within national borders in response to slow-onset changes[1,3,4].

Climate and environmental change continue to shape an increasingly mobile world[5]. In response, substantial scientific attention has been directed towards understanding the complex links between climate, environmental change, migration and displacement[6,7]. Surprisingly, however, there is as yet only an eclectic engagement across disparate subfields of migration studies, the potential for greater integration of environment within migration theories, and an insufficient knowledge of migration processes within larger coupled systems driving socio-environmental change[8–10] (see Box 1 for definitions of the key terms used in this Perspective).

Such shortcomings impede the formulation of appropriate policy responses to challenges associated with migration, for instance, through land-use planning, economic and agricultural development and sustainable urban growth[5,11–13]. These impediments are especially problematic for low- and middle-income regions that are expected to experience relatively strong climatic impacts, including those affecting rural smallholders and their interactions with the environment that can shape migration[5,14].

In this Perspective, we focus on important but understudied mobility dynamics—internal, domestic migration within rural landscapes—in both the sending and receiving systems (that is, origin and destination, respectively). Rural migration of smallholder farmers and livestock keepers in response to slow-onset climate and environmental change often precedes labour migration to urban areas or across national borders, and therefore has important implications for global

[1]Department of Human Dimensions of Natural Resources, Colorado State University, Fort Collins, CO, USA. [2]Graduate Degree Program in Ecology, Colorado State University, Fort Collins, CO, USA. [3]Department of Geographic and Environmental Sciences, University of Louisville, Louisville, KY, USA. [4]Natural Resource Ecology Laboratory, Department of Ecosystem Science and Sustainability, Colorado State University, Fort Collins, CO, USA. [5]Department of Atmospheric Science, Colorado State University, Fort Collins, CO, USA. [6]Department of Wildlife Management, Sokoine University of Agriculture, Morogoro, Tanzania. [7]Department of Forest and Environmental Economics, Sokoine University of Agriculture, Morogoro, Tanzania. [8]Center for International Earth Science Information Network (CIESIN), Columbia Climate School, Columbia University, New York, NY, USA. [9]Department of Environmental Studies, University of Colorado Boulder, Boulder, CO, USA. [10]Institute of Behavioral Science, CU Population Center, Department of Sociology, University of Colorado Boulder, Boulder, CO, USA. e-mail: jonathan.salerno@colostate.edu

BOX 1

Definition of key terms to aid in translation across disciplines

Rural–rural migration. Our focus in this Perspective, the permanent relocation of households from one rural area to another, often within national borders (that is, rural migration).

Land systems. Terrestrial socio-environmental systems where human and natural components interact through land use; they are also the focus of the interdisciplinary field of land system science[19].

Spatial telecouplings. Linkages or interdependencies between otherwise distinct landscapes or livelihoods, mediated by migrants or migration processes, and with implications for land use and land function[18,54].

Land function. Goods and services that are available to or support people and livelihoods from their land use at different scales across space and time[17].

Structural migration forces. Social, economic, political and ecological contexts that shape migration decisions (that is, macro- and meso-level factors).

Migration agency. Ability to make voluntary migration or non-migration decisions on the basis of individual (that is, micro-level) factors and context[9].

Non-migration. Remaining in place (that is, immobility).

Climate–environment–migration relationships. Ways in which climate and environmental processes (for example, rainfall or rangeland productivity) influence migration, and how migration in turn may affect the environment (for example, land-cover change), understanding that climate and environment are themselves interdependent[10].

Coupled models. Conceptual, analytical or process models that include linked submodels representing multiple scales or processes[50].

For recent reviews on climate–environment–migration relationships and theories, see refs. 6,10,35.

mobility dynamics[4]. We focus on a range of rural sending and receiving systems, from densely populated agricultural areas to thinly settled frontier regions. This framing understands that migration can mediate land-use intensification and expansion across various systems, and that households may engage multiple forms of migration within diversified livelihoods (for example, permanent migration or sending of temporary migrants for livestock keeping or labour)[15,16].

We approach climate–environment–migration relationships from the perspective of land system science, an interdisciplinary field that focuses on the multiscalar interactions of human and environmental processes evident through land use[17]. Our central argument is that greater attention must be directed towards rural migration, and that explicit integration of migration research and land system science can fill gaps in understanding while providing a firm foundation on which to address many future climate–environment–migration challenges. Our primary aim is to demonstrate useful conceptual and analytical tools for this integration, in part by engaging concepts of telecoupled systems and the interdependencies of structure–agency forces[9,18], which we illustrate using a conceptual agent-based model (ABM). As migration cuts across the UN 2030 Agenda for Sustainable Development[11], such efforts can inform science and policy around the trade-offs embedded in land systems change[19].

This Perspective is organized into five sections: an overview of migration in response to climate and environmental change, focusing on adaptation to slow-onset change; rural–rural migration as a linkage across telecoupled land systems, introducing environmental and decision thresholds; balancing structural and agentic factors that shape migration as a way to advance integrated science for understanding land change; the presentation of an agent-based modelling framework and the simulation of rural migration and land change as a means of exploring the above concepts; and future directions for addressing cross-scalar challenges and supporting sustainable and mobile futures. Notably, we use the ABM as a conceptual illustration of migration and land change in an agropastoralist system, with technical details provided in Supplementary Information.

Migration, climate and environmental change

Rural migration will become increasingly relevant as climate and environmental change reshape areas of marginal farming and rangeland[6,20,21]. The majority of empirical migration studies in low- and middle-income settings have focused on rural–urban migration, yet rural–rural migration is also an important adaptive strategy in the face of changes[22–24]. Moreover, migration processes are heterogeneous within landscapes and communities, meaning that different households make different decisions, even when exposed to the same climate–environment and political–economic contexts[4,25,26]. Indeed, impacts from climate and environmental stressors and diverse structural forces are mediated by unique household capacities (Fig. 1). For instance, case studies from across systems have found that rainfall variability or drought can act as a migration driver but often only for certain sub-populations, including the poor[27], those with social networks[28,29] or men[22,30]; conversely, these stressors may limit migration among other cohorts, such as women for the purpose of marriage or those seeking rural employment[16,31].

Existing migration theories provide some scope to consider such climate or environmental factors[10]. For instance, the work of Stark and Bloom[32] builds on individual utility maximization to enable household diversification amidst declines in land productivity or availability, including by adapting livelihood strategies through changes to crop and livestock practices or sending labour migrants. The livelihoods framework augments this thinking with a more comprehensive view of household capital assets and diversification strategies, and how migration may be used to balance environmental capital, risk and opportunity[33]. Migration systems theories consider social networks as key to facilitating flows, including out-migration to urban or international labour markets in response to environmental decline or hazard[34].

However, there is potential for further, more explicit integration of climate and environmental processes (for example, rainfall, vegetation structure, crop phenology and land-use intensification) into existing migration theories[10,35]. We contend that such integration can be facilitated through engagement with land system science, particularly when considering migration between rural areas[36,37]. We posit that land systems approaches can bring greater precision to the understanding of land change and its drivers, which may help to elevate generalized migration processes from the highly varied climate–environment–migration relationships evident in the empirical literature. Critically, such approaches must consider these relationships together with other factors that are acting at difference scales to influence migration (for example, political economy), the realization of which has been one of the most notable contributions from recent migration–environment scholarship[38].

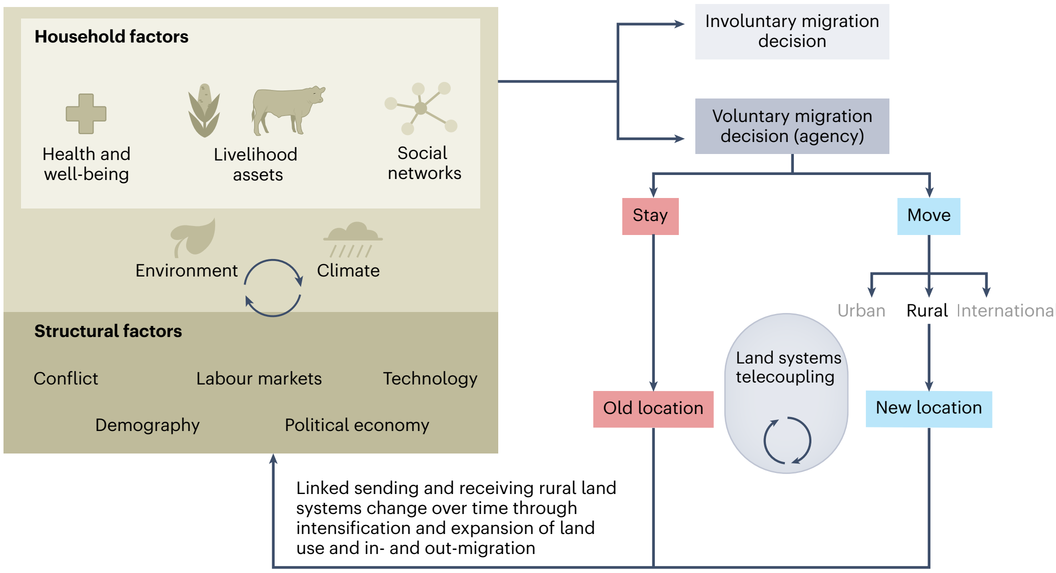

Fig. 1 | Conceptual model of rural–rural migration and land systems. Voluntary migration decision-making, or agency, includes both migration and non-migration and is shaped by structural, household and individual factors. Climate–environment factors intersect with structural forces and can act as migration triggers or create distinctions and/or inequalities between sending and receiving areas. Involuntary migration decisions include both forced migration and non-migration, but these are not our primary focus. Telecouplings link rural sending and receiving locations through social networks and flows of migrants and capital assets. Land change is shaped by these telecouplings and feedbacks among migration and land use. We operationalize this conceptual model into an interactive ABM to demonstrate the integration of migration theory and climate–environment factors with land system science. Forms of migration are adapted from refs. 4,38.

Permanent migration from rural sending areas to rural receiving areas constitutes a relatively small proportion of migrants globally, yet it remains a central adaptive strategy and an important driver of land change across smallholder systems, particularly in drylands[4,39]. Much of the early empirical work on rural frontier migration viewed these processes through a simplistic narrative associated with a general form of land degradation, which under-appreciated individual agency or decision-making and was only weakly predictive or generalizable[40]. This degradation narrative saw increasing densities of smallholder farmers and livestock keepers outstrip the productive capacity of land before out-migrating to less-densely populated areas; an extension of this thinking to include climate change yields predictions of drought- or flood-induced climate refugees, which as we note above is widely questioned[1]. Acknowledging harmful or unproductive narratives, degradation is more meaningfully defined as the decline or loss of the biological or economic productivity of land due to human activity[41]. Similarly, the concept of land function views the productivity of land systems as the goods and services that are available to or support people and livelihoods at different scales across space and time[17].

Land system science, through interrogation of land function, may support a more sophisticated integration of environmental and climate change within a conceptual and theoretical understanding of migration processes. Yet, as with migration science, the development of a unifying theory within land system science has remained elusive[42]. Meyfroidt and colleagues[36] have put forward a useful concept of middle-range theories, that is, contextual generalizations that articulate causal mechanisms leading to land systems change. Such generalizations that describe land-use expansion and intensification may hold particular relevance for rural migration, as smallholders increasingly engage with external markets in developing rural areas and frontiers[43]. Also relevant are livelihood transitions as households age and shift production strategies on the basis of available labour and in response to economic and political structures[39,44] or as households balance access to livestock and crop markets with land function via migration[15,23]. Most importantly, perhaps, is the theoretical focus on mechanisms of complex interactions that drive land-cover and land-use patterns, such as nonlinear dynamics[45] and spatio-temporal displacement of interactions[46].

Empirical work in land system science supporting contextual generalization and causal attribution has largely been pursued by incorporating multiple social and environmental components within grounded data analysis and modelling[17,47], providing potential frameworks for the testing of migration theory. Key areas of contribution involve reconciling various scales of remotely sensed data with in situ social and ecological data, which is essential in associating land-change signals with drivers, such as land-cover change linked to livelihood intensification, diversification and expansion[14] or to in- and out-migration[48]. Land-cover and -use signals may directly characterize land function, the measurement of which can potentially differentiate environmental, climate and social factors that shape diverse migration decisions and associated migration processes (for example, urban versus rural streams, return migration and non-migration). For instance, landscapes of sedentary agropastoralists may experience declining land function due to high stocking rates and subsequent declines in forage conditions and woody plant encroachment[39]. Phenological signals of these trends, potentially assessed alongside government settlement and protected-area policies, may illuminate past and future migration dynamics at various scales. Although challenges persist in resolving spatio-temporal scales of remote sensing, environmental and human data[49], there has been steady progress in reconciling the opportunities and limitations of such data integration[47]. In addition, whereas remote-sensing-based data products may be widely available at scale, data describing the human components in land systems (for example, from household surveys) are often resource-intensive to collect, even at a limited scale. Non-primary human data sources (for example, Demographic and Health Surveys (DHS), Integrated Public Use Microdata Series (IPUMS) and the WorldPop open population repository) may provide alternatives, but researchers must resolve issues of data quality, representativeness and scale to productively contribute to the development of modelling and theory[42,47].

Advanced land systems models have the potential to unpack multiscalar processes that shape land change—such as those linking distinct landscapes or organizational levels—although caution with these models is necessary to keep in check claims of validity and generalizability[42,50]. Computational process models, such as ABMs, may serve as particularly useful tools for interrogating interdependent top-down and bottom-up land system processes[36] that are inherent in rural migration, a feature that we aim to illustrate with our conceptual model exploration presented below. Coupling ABMs or decision models to models that capture phenomena at other scales represents potential productive future avenues for understanding land change. Examples include micro-scale ecosystem process models to illuminate the impacts of land-function change on migration, or macro-scale spatial equilibrium models to simulate migration flow responses to labour differentials within environmentally impacted market systems[50]. Such approaches must be attentive to linkages across spatial units and potential feedbacks (that is, telecouplings)[51].

Rural migration and telecoupled land systems

Migration featured prominently in early land-use and land-change research, for instance, as a proximate cause of expanding deforestation frontiers, with implicit links to resource-limited migrant sending areas or (re)settlement policies[36,52]. Advances towards a more integrative land system science involve explicit interactions of human and biophysical processes across scales[47,49,53], which we propose can provide a firm footing for a more explicit and systems-based understanding of rural migration.

Telecoupling describes linkages among land systems dynamics across space and time[18], representing a key area of engagement for migration research[37]. For instance, international migration links sending and receiving areas through social networks and remittance flows[34]. These telecouplings can shape landscapes in migration-sending areas, primarily through investment of financial capital altering rural land use[37] as well as adaptation to reduced household labour through more market-oriented production[44,54]. Likewise, households and communities sending migrants from higher density or degraded rural areas to lower-density rural or frontier regions maintain livelihood connections through similar relational and capital ties[23]. Such ties facilitate the flow or management of flexible livestock and agricultural assets along with human capital, which all mediate land use[55]. Trends or trajectories in, for example, livestock forage conditions and crop markets in a sending area will shape corresponding changes in a migrant-receiving area, mediated by livelihoods and land use. In addition, sending–receiving system interactions can have both negative and positive spillover effects at different scales[56], such as increased grazing pressure on protected areas adjacent to receiving areas or increased crop production supporting national-scale food security as land use in receiving areas intensifies. Importantly, a land system science perspective seeks to understand feedbacks among migrant-linked sending, receiving and spillover systems that together shape socio-environmental change[36,37].

We posit that such feedbacks will become increasingly important as climate and environmental changes affect livelihoods and risk in potential sending areas and as prospective receiving or frontier areas shift and dwindle, so-called closing frontiers[37]. Migration thresholds represent a key concept for future development in the context of telecoupled systems. Adaptive migration can be conceptualized as a decision that is prompted when a threshold is reached[57], shaped by the influence of social and environmental factors that pose risk or opportunity[14]. Such factors accumulate, leading up to a threshold, beyond which decisions are made, probably first to adapt in situ livelihoods and subsequently to migrate. The threshold concept has described individual migration decision-making, such as cumulative environmental stress triggering a person to move. Thresholds also describe a 'tipping point' in a mobility system, beyond which population-level shifts become nonlinear, which is particularly relevant to adaptation and climate policy[58,59]. Our interests are in slow-onset climate and environmental changes that lead to migration thresholds among rural migrants, in addition to the occurrence of these and other structural migration factors, such as political economy, and their balance with individual decisions or agency (see next section). It follows that such changes and their associated migration thresholds can thus be predictive of coupled dynamics in rural receiving areas, a concept that we seek to illustrate with our conceptual ABM presented below.

More precise understanding of land change within telecoupled migration systems, including migration thresholds associated with environmental and climate factors, can support improved causal attribution[51,60]. Following Liu and colleagues[18], the key components of telecoupling that influence socio-environmental outcomes are: spatially distinct systems, defined as sending, receiving and spillover systems that are impacted by linked or telecoupled dynamics; flows, defined as the movement(s) of material (for example, migrants or capital) or immaterial (for example, information) elements between systems; agents (or actors), defined as entities such as people or institutions whose actions directly or indirectly influence flows; causes, defined as factors that shape agent actions or flows, either directly or indirectly, such as adverse trends in rainfall, temperature or land function associated with rural migration or non-migration[23,30,48]; and effects, defined as the socio-environmental consequences or outcomes of telecoupled processes, which occur across scales and often include complex dynamics such as feedbacks and nonlinearities or thresholds, among others. Specified in this way, the telecoupling framework can articulate multifactor influences on migration decisions, and how those decisions propagate across sending and receiving areas. A key point is that we view rural migration telecouplings as linking regions and landscapes, rather than much of the existing work that addresses global or larger-scale telecouplings.

Structure and agency in migration decisions

Recent work has articulated a tension in scholarship between, on the one hand, a focus on agency of migrants, particularly in traditional land-change science, and, on the other, a focus on causal structural factors such as environment and political economy, dominant in human geography subfields[9,61]. Migration must be understood as a dynamic, heterogeneous process[6], and whereas some migration may be reduced to an adaptive decision by autonomous agents, such decisions are structured by context[37,62]. Even so, and despite the recent surge of migration–environment research described above, there has been only a passing engagement of structure–agency balance within broader migration theories[9]. Pathways towards a better understanding and prediction of migration processes likely involve addressing structure–agency relationships in theoretically informed empirical frameworks[10,35,41].

Recent conceptual thinking has shown promise in articulating migrant agency as integrated and interdependent with structural forces. For instance, de Haas[61] proposes a 'meta-theoretical framework' in which agency in migration decision-making is viewed as a function of individuals' aspirations and capabilities, which are shaped by structures such as policy, wealth or conflict differentials. Notably, this thinking enables the prediction of outcomes that include forced and voluntary non-migration and migration alike[41,54]. Such framing seeks to avoid overly deterministic assumptions of both functionalist (for example, neoclassical, utility-maximizing or push–pull) and structural theories (for example, political–economic or world systems), in other words seeking a balance across multiscale drivers that have clear relevance in diverse migration systems. It remains to be seen whether, as described by de Haas[61], the past qualitative and quantitative failures to capture these multiscale factors and their interplay can be overcome to adequately understand and predict migration outcomes as meaningfully embedded within broader social change. We see environmental and climate change as viewed in land systems (or socio-environmental

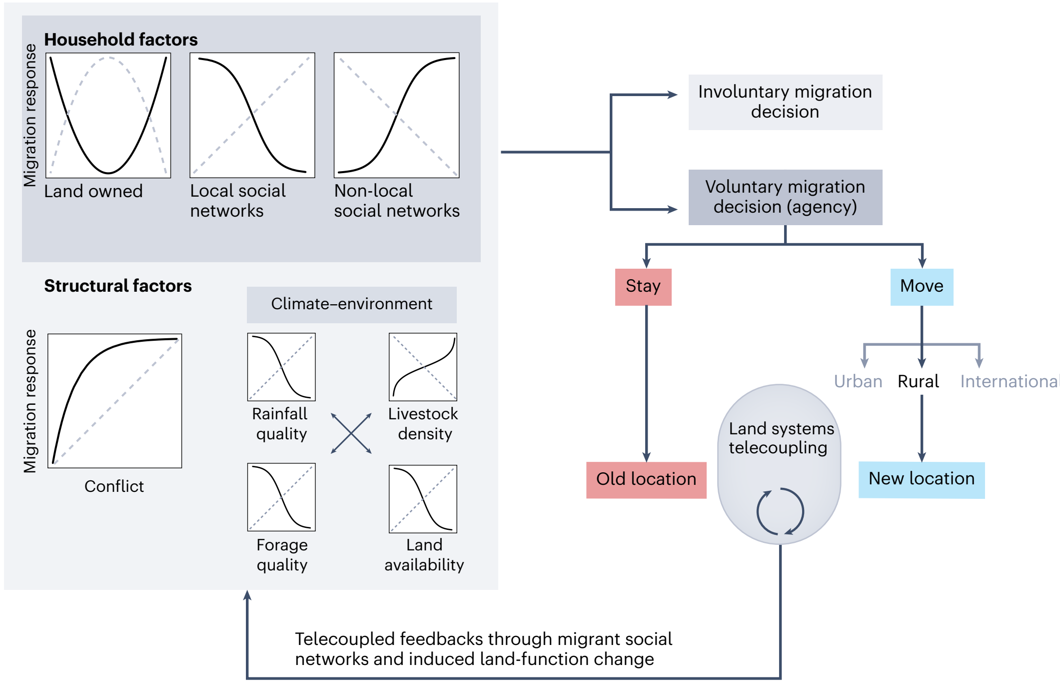

Fig. 2 | Decision complexity underlying the MLSM. The ABM is built on candidate, theorized relationships between predictive factors and migration outcomes, which are represented as dark response curves on the left, within the more general decision framework presented in Fig. 1. Note that the model accounts for the interactions of these factors that influence migration decisions, and then subsequent feedbacks whereby migration influences structural factors of both the sending and receiving systems. The model enables alternative response curves (for example, dashed lines) or additional factors to be tested (for example, labour markets or amenities), potentially showing emergent interactions or system-level outcomes. Climate–environment factors interact to shape structural differences between the sending and receiving sites, and are assessed together with other factors at each iteration (that is, agents assess the relative benefits of multiple candidate locations compared with their current location). An adapted model trained on empirical data can be used to assess theorized relationships or the relative influence of diverse decision factors.

systems) to be central to this deeper understanding; specifically, such framing can advance stronger theoretical–empirical linkages[35] and our understanding of complex processes such as emergent and nonlinear dynamics within migration systems[10].

Because land systems science offers developing tools and theories to unpack causes and consequences associated with land change, there is significant potential to better quantify and understand climate–environment–migration linkages, thus articulating their various roles as structural and mediating processes. We propose one such method of sensitivity analysis to do just this with the conceptual ABM below. Indeed, quantifying multiscalar and multifactor causes of land change, for instance, declining land function or the degradation of drylands in agropastoral systems, enables us to counter deterministic explanations of drivers and impacts of rural migration. And as discussed above, this enables us to define decision mechanisms for associating specific environmental signals or trends with an individual's or a household's migration decision (that is, threshold), which is contingent on their aspirations and capabilities that amount to agency.

Modelling rural migration and land change

We operationalize our conceptual model (Fig. 1) into a simple ABM—the migration–land systems model (MLSM)—to illustrate the integration of migration and land systems fields, specifically through a discussion of (1) sending- and receiving-system telecouplings and (2) individual and structural decision-making factors. The intent is to propose future avenues for theory development and theory testing[35], with an eye towards understanding system complexity[36,47,50]. To this end we present the MLSM as an interactive tool to demonstrate the synthesis of concepts and facilitate future dialogue (see stylized experiments linked through Supplementary Information). We situate this exercise in the rapidly changing landscapes and agropastoralist migration system of East Africa, although our goals are conceptual and illustrative rather than intending to simulate or recreate empirical dynamics[48].

ABMs are useful and powerful tools for explaining large-scale processes through the behaviour of individual- or agent-scale interactions with their surroundings[63], and as such are particularly well-suited for exploring climate–environment–migration relationships[64]. ABMs have been used in land change science, but those applications lack a grounding in theory and have been limited by a reliance on economic decision factors over social processes[65]. Moreover, the limited number of ABMs that explore migration under-engage with environmental dynamics and insufficiently capture system complexity, such as through feedbacks or telecoupled processes[64], although there are notable exceptions[48,66,67].

Migration and land change in a conceptual ABM

We present the MLSM to illustrate simplified migration dynamics, drawing on an agropastoralist system in Tanzania, East Africa. Rural migration (that is, permanent relocation from one rural area to another) and associated land use is the most significant driver of land change in Tanzania[23,43]. Accelerated by successive droughts since the 1970s, farmers and herders have expanded from areas of high rural density or marginal productivity in the north to low-density areas in central and southern regions[68]. Whereas migration decisions are strongly influenced by environmental factors (for example, available land or rainfall) and mediated by social networks, the resulting migration patterns are shaped by other structural forces, such as settlement policies, inter-ethnic conflict and developing cash-crop markets[23,68]. The agropastoralist expansion is described as 'leapfrog migration'[55], where households migrate to the edge of frontier areas and settle to conduct rain-fed farming and central-place grazing; as population density increases with further in-migration, some households then

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out-migrate to more distant, less-settled areas when productivity of the landscape can no longer support their livelihoods. However, as settlement subsumes the remaining frontier areas, there is increasing migration within and among moderate- to higher-density rural areas. Owing to rapid urbanization and rural land change, along with highly uncertain climate futures, Tanzania has been elevated as a focal case for future climate and migration policy[69].

Model simulations are conducted to help conceptualize migration-mediated landscape telecouplings and to explore how climate–environment factors and individual agency within the sending system can drive land function changes in the receiving systems. To do this, the model aggregates factors into an agent-level decision function—agents assess candidate destination options against their current location via social networks—with each factor having a tunable influence on migration outcomes, drawn, for instance, from theory or empirical observations within the migration literature (Fig. 2). Notably, we consider interacting climate–environment factors to be structural[9,61] because they shape differentials between sending and receiving systems, but we acknowledge their heterogeneity and that they may act variably as triggers or exogenous factors in different systems[38]. Supplementary Information presents a model overview, technical description and details of the simulations presented below.

Telecouplings and system thresholds

We conducted simulations to help illustrate how migration-mediated telecouplings can shape land function and subsequent migration in the context of environmental variability and slow-onset changes, while being attentive to emergent thresholds (Figs. 2 and 3). Relative to the receiving system, the sending system was initiated to experience three scenarios of higher, lower and drought-onset rainfall patterns (Fig. 3a–c). For each of these rainfall scenarios we monitored agent contentedness in the sending system (that is, individual migration decisions; Fig. 3d–f) and land function changes in the receiving system (Fig. 3g–i) for three levels of social network strength (that is, information sharing across systems).

The simulations illustrate migration complexity and how land-function effects via telecouplings may emerge under certain rainfall and social network conditions. Whereas agents remain content in the sending system with minimal out-migration observed under high rainfall conditions (Fig. 3a,d,g), their decisions are patterned by the strength of social networks under low rainfall and drought-like conditions. There is remarkably low sending-system contentedness at the low-network level, which equates to forced non-migration (Fig. 3e,f). Land-function effects in the receiving sites (that is, increase in biomass grazed) respond to declining rainfall in the sending sites. When the sending sites experience low rainfall (Fig. 3b), land function changes rapidly in receiving sites before stabilizing (Fig. 3h), due to in-migration of people and livestock; that is, land change in receiving areas is coupled with rainfall in the sending site, even enabling land-change effects in the receiving site to be forecasted by environmental conditions in the sending site. Social network strength amplifies these land-function responses in the low rainfall scenario, suggesting that the mediating effects of social ties vary with environmental and climate stress. When the sending site experiences a slow-onset drought-like rainfall change (Fig. 3c), multiple threshold-type responses in coupled land function are evident in the receiving site (Fig. 3i).

In this particular illustration, telecouplings between systems as viewed through impacts on land function are sensitive to climate–environment change. These dynamics can be replicated by readers through an interactive, simplified web-based model (Supplementary Information). In the model's current configuration, rainfall acts a strong driver of flows of migrants and cattle and the subsequent effects on land function. However, even in this simplified form, social networks mediate system couplings in different ways, seemingly most strongly under low rainfall conditions, but not under slow-onset drought conditions. That is, strong social networks under the lowest rainfall conditions in the sending site forecasted the most prominent land-function impacts in the receiving site.

Moreover, the model enables further interrogation of emergent threshold responses. Initial migrant flows (within the first few months) are observed in high- and low-rainfall scenarios with moderate to strong social networks, followed by stabilization (Fig. 3g,h). However, as we model migration decisions as the outcomes of cumulative information and experiences, the drought-onset scenario causes multiple decision thresholds to be breached as drought stress accumulates, which are observed through land-function impacts in the receiving system (Fig. 3i). Notably, these dynamics emerge from the underlying theorized or conceptualized relationships among the multiple factors that

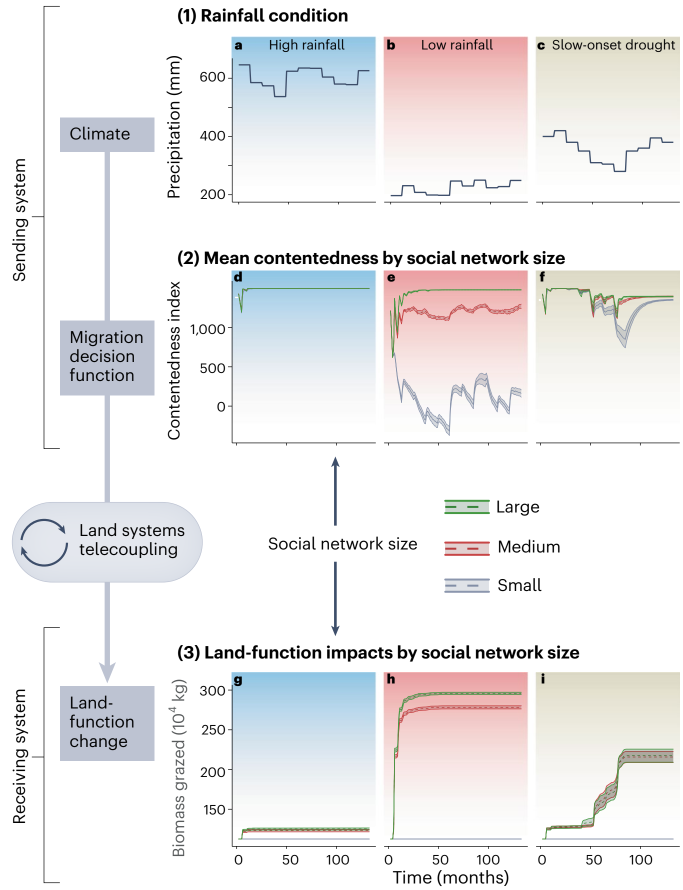

Fig. 3 | ABM simulations exploring system telecouplings and thresholds under various climate scenarios. Agents are distributed on patches with available biomass in the sending (high-density) and receiving (low-density) systems. Each month, agents may experience a decline in cumulative contentedness that results from a combination of unfavourable structural conditions (for example, rainfall declines and effects on biomass, experience of conflict) interacting with agent-specific factors (for example, land and livestock ownership, social capital). Below a minimum contentedness threshold, agents assess the conditions in multiple alternative patches, via their social networks, to inform a decision of migration (or non-migration). **a**–**c**, Simulations impose high (**a**), low (**b**) and slow-onset or drought-like (**c**) rainfall scenarios in the sending system. **d**–**f**, Contentedness is tracked across the scenarios of high (**d**), low (**e**) and drought-like (**f**) rainfall for agents with high (green), moderate (red) and no social networks (grey); agents without social networks experience effective non-migration and the lowest levels of contentedness but only in lower rainfall conditions (**e**). **g**–**i**, Land-function impacts in the receiving system are influenced by sending-system rainfall (high (**g**), low (**h**) and drought-like (**i**)) and mediated by social networks as translated through migrant decisions; threshold dynamics are coupled to the sending-system rainfall and migrant decisions, particularly under slow-onset drought (**i**).

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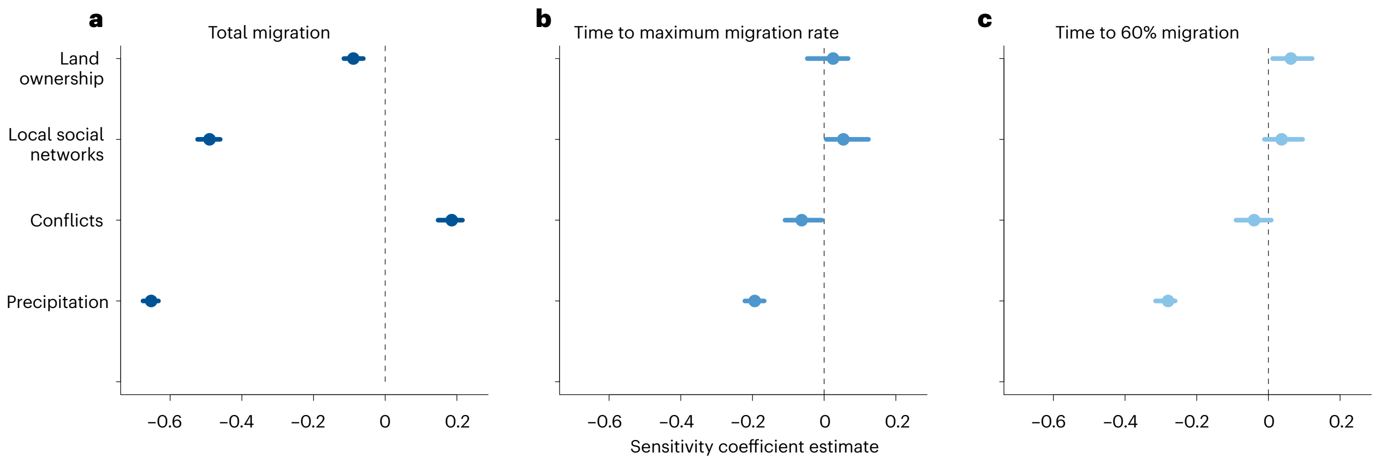

Fig. 4 | ABM sensitivity results to assess the relative structure–agency influences on migration outcomes. a–**c**, Standardized regression coefficients for two patch- or system-specific structural factors (mean annual rainfall and social conflict) and two agency-related factors (individual land ownership and individual local social networks) from 500 unique MLSM runs to predict total migration outcomes (**a**), the time of maximum migration rate (**b**) and the time taken for 60% of total migrations to occur (**c**). Coefficient values from the analysis indicate the sensitivity of migration outcomes to variation in the key factors, as estimated via regression models fitted to unique combinations of migration factor values generated from Latin hypercube sampling of factor distributions that reflect natural ranges. Coefficient estimates are plotted with 95% confidence intervals.

shape the migration outcomes shown in Fig. 2. We posit that the MLSM or similar models can be useful in generating candidate hypotheses for testing in empirical contexts[48,67], and therefore help to facilitate greater theoretical engagement with environmental and climatic processes[10,35].

Relative influence of structure and agency

We illustrate a sensitivity analysis of simulated migration events as a candidate method to examine how variation in structural and agency-related factors influences migration decisions and systems outcomes, which offers general insight into examining structure–agency dynamics more broadly. We monitored how the magnitude and rate of migration within the MLSM are sensitive to variation in two structural factors (social conflict and rainfall differentials) and two agency-related factors (individually varying land ownership and local social networks) operating within the sending system (Supplementary Information). The analysis yields coefficient estimates that indicate the relative influence of specific factors on migration outcomes, thereby enabling interpretation of structure and agency influences while embracing system complexity.

In our conceptual model, both structural and agency factors drive the total number of long-distance migrants, with rainfall, followed by the strength of local social networks, having the strongest influence (Fig. 4a). Total migration increases with declines in rainfall and declines in local social network strength. Both measures of migration rate (Fig. 4b,c) were only moderately sensitive to the four predictors. Larger migration volumes occurred later in the simulation when rainfall declined in the sending site, with other variables showing relatively weak and uncertain relationships.

The point of the sensitivity exercise presented here is not to infer a diminished role for certain factors, such as an individual's own capabilities or a population's experience with social conflict, in driving migration decisions. Instead, the exercise demonstrates that a model conceptualized following a specific migration system, or trained on empirical data, can be used to explore structure–agency dynamics and the relative influence of a variety of factors. Moreover, insofar that the decision function captures both the complexity of interacting factors and the notable stochasticity of migration responses, such modelling and evaluation approaches may represent significant gains over a standard analysis of migration drivers (for example, via linear regression) when applied in empirical contexts[48,61].

Broader implications of the conceptual ABM

As we aim to demonstrate using the MLSM above, such systems modelling has unique potential to advance the development of theory for climate–environment–migration linkages[64], while fostering productive synthesis among the migration and land system sciences. Central to these potential gains is a more explicit understanding of the complexity of underlying processes, such as interdependencies among rainfall, conflict, individual capabilities and land function, that together influence various forms of migration[50]. Recent advances with ABM approaches have demonstrated productive avenues with similar decision complexity informing migration, for instance, by modelling environmental stress or hazard that shapes livelihood options and the likelihood (or not) of rural return migration from urban centres, in systems where labour migration dominates[48,67]. Our illustration using a conceptual agropastoralist system is relevant to drylands globally, which cover more than 40% of the Earth's inhabited surface and where landscape sustainability is inherently tied to farming, livestock-keeping and migration[39]. Although our ABM aims to highlight land system linkages across rural sending and receiving systems that are associated predominantly with agropastoralist livelihoods, it is feasible that extensions of the model could capture the urban labour migration of individuals to support household diversification and herd maintenance (for example, in West African systems[15]) or rural non-farm migration where urban labour markets or infrastructure is limiting (for example, in other regions of East Africa[16]).

More broadly, as frontiers dwindle across diverse rural systems, migration will continue to shape land-use intensification in various ways and in response to a suite of migration drivers and system couplings. Furthermore, shifts in global economic and political forces, as evident in Amazonia in recent years[70], illustrate how rural migration rapidly responds to structural forces, opening opportunities in newly accessible rural areas and with significant consequences for land systems (a point we revisit below and in conclusion).

Anticipating and managing future land use is central to sustainability planning and efforts that aim at predicting, mitigating and adapting to climate change[19]. However, abrupt regime shifts in land systems can invalidate the predictions of future land use emerging from models and theory that inadequately engage the ongoing global redistribution and growth of human populations[30]. Our simulation illustrates how, in the context of slow-onset changes, migration can serve as a conduit for precipitating regime shifts in telecoupled landscapes, as seen through threshold responses in land function. Simultaneously, it shows migration as an outcome of interactions among diverse structural-, agency- and social-network-related factors, further underscoring the complexity and interdependencies of migration and the resulting land system changes.

The ability to integrate cross-scale and -disciplinary explanatory variables is a recognized strength of the ABM approach[36,64]. While our model leverages this strength, it also refines and centres the representation of key less-tangible drivers of migration, such as contentment and social embeddedness[54,61]. Migration is widely accepted as an adaptive strategy in the face of accelerating environmental change, yet there is also growing recognition that the importance communities attach to culture, livelihood and sense of place may override the adaptive advantages of migration, leading to voluntary non-migration[4,37]. In our model, the ability to control the strengths of variables that together contribute to an agent's level of contentment enables the testing of hypotheses related to the emergence of complex forms of vulnerability and land transformations that result from non-migration or low-agency migrations[41].

Future directions for meeting global challenges

At present, significant attention is directed towards the climate–environment–migration nexus. Although migration fields work to move beyond the framing of climate refugees[1,35], much of the science still underappreciates the complexity of migration within broader systems, including the dynamic nature of people and land use[21,37]. Such framing restricts the ability to make predictions and inform policy solutions to associated challenges[9,13]. Our central aims in this paper are to elevate rural migration to help facilitate a greater integration of migration and land system science. Doing so may help to promote reciprocal advancements, including a better understanding of multiscalar socio-environmental dynamics that involve migration while embedding climate–environment processes within migration theory.

This integration will help to articulate the cross-cutting nature of rural migration with multiple, interacting dimensions of sustainability, including poverty alleviation, food security, land and biodiversity conservation and climate change adaptation and mitigation[11]. Migration often involves land systems or socio-environmental trade-offs, which are increasingly telecoupled across sending, receiving and spillover or external systems[19,39,56]. The complexity of migration processes that we describe points to the need for better unpacking of migration-linked trade-offs within land systems, especially as they relate to global sustainability policy initiatives such as the Sustainable Development Goals (SDGs), the Intergovernmental Panel on Climate Change (IPCC), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Half-Earth Project, and in particular as global drylands continue to expand under current and future climate change. For example, comprehensive decarbonization pathways notably rely on the extensive transformation of rural agricultural landscapes to forested landscapes, whether or not they may have been previously forested[36]. This and other types of extensive policy-driven landscape change in the service of sustainability invite critical attention from the migration community. Future research agendas have much to offer when focused explicitly on migration intersections across sustainability challenges, many of which originate with changing land use and land function within larger coupled systems[19].

The simulation of complex migration processes remains difficult, particularly when the goal is to project future migration amidst significant uncertainty. However, recent work demonstrates the potential for and utility of various approaches, from structuring broad narratives around urbanization, development, governance and climate change trajectories (for example, the Shared Socioeconomic Pathways) to predictive modelling frameworks[4,12,67,69]. Advanced land systems models have a clear role to play, yet challenges posed by feedbacks and other multiscalar dynamics, such as we describe with telecouplings, remain evident, as do problems with validation and broader relevance[50,63]. Coupling together models built at distinct scales, such as ecosystem and migrant-agent models, as well as to climate or development scenarios, may help to advance experimentation and simulation of interdependent top-down and bottom-up processes. Indeed, these efforts will require embracing the tension between structure and agency if we are to understand their varying influence on migration and non-migration across the range of volition.

Migration futures will likely hold new realities. We emphasize the importance of an expanded understanding regarding the various forms of migration[59,61], and we highlight rural migration as essential within this future thinking. Indeed, urban–rural migration has proved sensitive to recent economic shocks, as shown during the COVID-19 pandemic, and future climatic changes such as sea-level rise have the potential to displace coastal urban residents to rural interiors[4], although not uniformly[67]. Such population shifts have significant implications for rural livelihoods and land systems, as do policy changes that alter land access and rural migration calculus like those we note above in the Brazilian Amazon[70]. Yet future environmental and social changes that act as migration drivers must be balanced with in situ adaptation and agency[48,67], and a systems-based approach for resolving bottom-up and top-down forces will be critical for shedding light on the complexity that is inherent in future migration. Despite uncertainties around form and impact, integrated migration and land system science approaches will be essential for unpacking the complexities and informing policy challenges around migration and land change.

References

1. Black, R., Bennett, S. R. G., Thomas, S. M. & Beddington, J. R. Migration as adaptation. *Nature* **478**, 447–449 (2011).
2. Gemenne, F. Why the numbers don't add up: a review of estimates and predictions of people displaced by environmental changes. *Glob. Environ. Change* **21** (Suppl. 1), S41–S49 (2011).
3. Adger, W. N. et al. Focus on environmental risks and migration: causes and consequences. *Environ. Res. Lett.* **10**, 060201 (2015).
4. Rigaud, K. K. et al. *Groundswell: Preparing for Internal Climate Migration* (World Bank, 2018); http://hdl.handle.net/10986/29461
5. Birkmann, J. et al. in *Climate Change 2022: Impacts, Adaptation and Vulnerability* (eds Pörtner, H.-O. et al.) 1171–1274 (IPCC, Cambridge Univ. Press, 2022).
6. Borderon, M. et al. Migration influenced by environmental change in Africa: a systematic review of empirical evidence. *Demogr. Res.* **41**, 491–544 (2019).
7. Hoffmann, R., Šedová, B. & Vinke, K. Improving the evidence base: a methodological review of the quantitative climate migration literature. *Glob. Environ. Change* **71**, 102367 (2021).
8. Eakin, H. et al. in *Rethinking Global Land Use in an Urban Era* (eds Seto, K. C. & Reenberg, A.) 141–161 (MIT Press, 2014).
9. Jokisch, B. D., Radel, C., Carte, L. & Schmook, B. Migration matters: how migration is critical to contemporary human–environment geography. *Geogr. Compass* **13**, e12460 (2019).
10. Hunter, L. M. & Simon, D. H. Time to mainstream the environment into migration theory? *Int. Migr. Rev.* https://doi.org/10.1177/01979183221074343 (2022).
11. Adger, W. N., Fransen, S., Safra de Campos, R. & Clark, W. C. Migration and sustainable development. *Proc. Natl Acad. Sci. USA* **121**, e2206193121 (2024).
12. Clement, V. et al. *Groundswell Part 2: Acting on Internal Climate Migration* (World Bank, 2021).
13. Stojanov, R., Rosengaertner, S., de Sherbinin, A. & Nawrotzki, R. Climate mobility and development cooperation. *Popul. Environ.* **43**, 209–231 (2021).

14. Hoffmann, R., Wiederkehr, C., Dimitrova, A. & Hermans, K. Agricultural livelihoods, adaptation, and environmental migration in sub-Saharan drylands: a meta-analytical review. *Environ. Res. Lett.* **17**, 083003 (2022).
15. Turner, M. D., McPeak, J. G. & Ayantunde, A. The role of livestock mobility in the livelihood strategies of rural peoples in semi-arid West Africa. *Hum. Ecol.* **42**, 231–247 (2014).
16. Mueller, V., Schmidt, E., Lozano-Gracia, N. & Murray, S. *Household and Spatial Drivers of Migration Patterns in Africa: Evidence from Four Countries* (Department for International Development, Government of the United Kingdom, 2016).
17. Verburg, P. H., Erb, K.-H., Mertz, O. & Espindola, G. Land system science: between global challenges and local realities. *Curr. Opin. Environ. Sustain.* **5**, 433–437 (2013).
18. Liu, J. et al. Framing sustainability in a telecoupled world. *Ecol. Soc.* **18**, 19 (2013).
19. Meyfroidt, P. et al. Ten facts about land systems for sustainability. *Proc. Natl Acad. Sci. USA* **119**, e2109217118 (2022).
20. Wiederkehr, C., Beckmann, M. & Hermans, K. Environmental change, adaptation strategies and the relevance of migration in Sub-Saharan drylands. *Environ. Res. Lett.* **13**, 113003 (2018).
21. Hermans, K., Müller, D., O'Byrne, D., Olsson, L. & Stringer, L. C. Land degradation and migration. *Nat. Sustain.* **6**, 1503–1505 (2023).
22. Henry, S., Schoumaker, B. & Beauchemin, C. The impact of rainfall on the first out-migration: a multi-level event-history analysis in Burkina Faso. *Popul. Environ.* **25**, 423–460 (2004).
23. Salerno, J. Migrant decision-making in a frontier landscape. *Environ. Res. Lett.* **11**, 044019 (2016).
24. Grace, K., Hertrich, V., Singare, D. & Husak, G. Examining rural Sahelian out-migration in the context of climate change: an analysis of the linkages between rainfall and out-migration in two Malian villages from 1981 to 2009. *World Dev.* **109**, 187–196 (2018).
25. Barnett, J. & Adger, W. N. Mobile worlds: choice at the intersection of demographic and environmental change. *Annu. Rev. Environ. Resour.* **43**, 245–265 (2016).
26. Gemenne, F. & Blocher, J. How can migration serve adaptation to climate change? Challenges to fleshing out a policy ideal. *Geogr. J.* **183**, 336–347 (2017).
27. Gray, C. L. & Mueller, V. Natural disasters and population mobility in Bangladesh. *Proc. Natl Acad. Sci. USA* https://doi.org/10.1073/pnas.1115944109 (2012).
28. Nawrotzki, R. J., Runfola, D. M., Hunter, L. M. & Riosmena, F. Domestic and international climate migration from rural Mexico. *Hum. Ecol.* **44**, 687–699 (2016).
29. Riosmena, F., Nawrotzki, R. & Hunter, L. Climate migration at the height and end of the Great Mexican Emigration Era. *Popul Dev. Rev.* **44**, 455–488 (2018).
30. Mueller, V., Gray, C. & Kosec, K. Heat stress increases long-term human migration in rural Pakistan. Nat. *Clim. Change* **4**, 182–185 (2014).
31. Gray, C. & Mueller, V. Drought and population mobility in rural Ethiopia. *World Dev.* **40**, 134–145 (2012).
32. Stark, O. & Bloom, D. E. The new economics of labor migration. *Am. Econ. Rev.* **75**, 173–178 (1985).
33. de Sherbinin, A. et al. Rural household demographics, livelihoods and the environment. *Glob. Environ. Change* **18**, 38–53 (2008).
34. Massey, D. S., Arango, J., Hugo, G., Kouaouci, A. P. & Pellegrino, A. *Worlds in Motion: Understanding International Migration at the End of the Millennium* (Oxford Univ. Press, 1998).
35. de Sherbinin, A. et al. Migration theory in climate mobility research. *Front. Clim.* https://doi.org/10.3389/fclim.2022.882343 (2022).
36. Meyfroidt, P. et al. Middle-range theories of land system change. *Glob. Environ. Change* **53**, 52–67 (2018).
37. Radel, C. et al. Migration as a feature of land system transitions. *Curr. Opin. Environ. Sustain.* **38**, 103–110 (2019).
38. Black, R. et al. The effect of environmental change on human migration. *Glob. Environ. Change* **21**, S3–S11 (2011).
39. Liao, C., Agrawal, A., Clark, P. E., Levin, S. A. & Rubenstein, D. I. Landscape sustainability science in the drylands: mobility, rangelands and livelihoods. *Landsc. Ecol.* **35**, 2433–2447 (2020).
40. Morrissey, J. Rethinking the debate on environmental refugees: from maximilists and minimalists to proponents and critics. *J. Polit. Ecol.* **19**, 36–49 (2012).
41. Hermans, K. & McLeman, R. Climate change, drought, land degradation and migration: exploring the linkages. *Curr. Opin. Environ. Sustain.* **50**, 236–244 (2021).
42. Rindfuss, R. R., Walsh, S. J., Turner, B. L., Fox, J. & Mishra, V. Developing a science of land change: challenges and methodological issues. *Proc. Natl Acad. Sci. USA* **101**, 13976–13981 (2004).
43. Salerno, J., Mwalyoyo, J., Caro, T., Fitzherbert, E. & Mulder, M. B. The consequences of internal migration in Sub-Saharan Africa. *BioScience* **67**, 664–671 (2017).
44. VanWey, L. K., Guedes, G. R. & D'Antona, A. O. Out-migration and land-use change in agricultural frontiers: insights from Altamira settlement project. *Popul. Environ.* **34**, 44–68 (2012).
45. Lambin, E. F. & Meyfroidt, P. Land use transitions: socio-ecological feedback versus socio-economic change. *Land Use Policy* **27**, 108–118 (2010).
46. Liu, J. et al. in *Rethinking Global Land Use in an Urban Era* (eds Seto, K. C. & Reenberg, A.) 119–140 (MIT Press, 2014).
47. Kugler, T. A. et al. People and Pixels 20 years later: the current data landscape and research trends blending population and environmental data. *Popul. Environ.* **41**, 209–234 (2019).
48. Entwisle, B., Verdery, A. & Williams, N. Climate change and migration: new insights from a dynamic model of out-migration and return migration. *Am. J. Sociol.* **125**, 1469–1512 (2020).
49. Turner, B. L., Lambin, E. F. & Reenberg, A. The emergence of land change science for global environmental change and sustainability. *Proc. Natl Acad. Sci. USA* **104**, 20666–20671 (2007).
50. Verburg, P. H. et al. Beyond land cover change: towards a new generation of land use models. *Curr. Opin. Environ. Sustain.* **38**, 77–85 (2019).
51. Busck-Lumholt, L. M. et al. Telecoupling as a framework to support a more nuanced understanding of causality in land system science. *J. Land Use Sci.* **17**, 386–406 (2022).
52. Geist, H. J. & Lambin, E. F. Proximate causes and underlying driving forces of tropical deforestation. *BioScience* **52**, 143–150 (2002).
53. Gutman, G. et al. (eds) *Land Change Science: Observing, Monitoring and Understanding Trajectories of Change on the Earth's Surface* Vol. 6 (Springer, 2004).
54. Sakdapolrak, P. et al. Translocal social resilience dimensions of migration as adaptation to environmental change. *Proc. Natl Acad. Sci. USA* **121**, e2206185120 (2024).
55. Charnley, S. Environmentally-displaced peoples and the cascade effect: lessons from Tanzania. *Hum. Ecol.* **25**, 593–618 (1997).
56. Liu, J. et al. Spillover systems in a telecoupled Anthropocene: typology, methods, and governance for global sustainability. *Curr. Opin. Environ. Sustain.* **33**, 58–69 (2018).
57. Bardsley, D. K. & Hugo, G. J. Migration and climate change: examining thresholds of change to guide effective adaptation decision-making. *Popul. Environ.* **32**, 238–262 (2010).
58. Adger, W. N., Lorenzoni, I. & O'Brien, K. L. (eds) *Adapting to Climate Change: Thresholds, Values, Governance* (Cambridge Univ. Press, 2009).

59. McLeman, R. et al. Conceptual framing to link climate risk assessments and climate-migration scholarship. *Climatic Change* **165**, 24 (2021).
60. McLeman, R. & Smit, B. Migration as an adaptation to climate change. *Climatic Change* **76**, 31–53 (2006).
61. de Haas, H. A theory of migration: the aspirations–capabilities framework. *Comp. Migr. Stud.* **9**, 8 (2021).
62. Abel, G. J., Brottrager, M., Crespo Cuaresma, J. & Muttarak, R. Climate, conflict and forced migration. *Glob. Environ. Change* **54**, 239–249 (2019).
63. Klabunde, A. & Willekens, F. Decision-making in agent-based models of migration: state of the art and challenges. *Eur. J. Popul.* **32**, 73–97 (2016).
64. Thober, J., Schwarz, N. & Hermans, K. Agent-based modeling of environment-migration linkages: a review. *Ecol. Soc.* **23**, 41 (2019).
65. Groeneveld, J. et al. Theoretical foundations of human decision-making in agent-based land use models—a review. *Environ. Model. Softw.* **87**, 39–48 (2017).
66. Kniveton, D., Smith, C. & Wood, S. Agent-based model simulations of future changes in migration flows for Burkina Faso. *Glob. Environ. Change* **21**, S34–S40 (2011).
67. Bell, A. R. et al. Migration towards Bangladesh coastlines projected to increase with sea-level rise through 2100. *Environ. Res. Lett.* **16**, 024045 (2021).
68. Galaty, J. G. in *Production and Autonomy: Anthropological Studies and Critiques of Development* (eds Bennett, J. W. & Bowen, J. R.) 163–184 (Univ. Press of America, 1988).
69. Rigaud, K. K., de Sherbinin, A., Jones, B. R., Arora, A. & Adamo, S. *Groundswell Africa: A Deep Dive on Internal Climate Migration in Tanzania* (World Bank, 2021).
70. Peres, C. A., Campos-Silva, J. & Ritter, C. D. Environmental policy at a critical junction in the Brazilian Amazon. *Trends Ecol. Evol.* **38**, 113–116 (2023).

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The authors declare no competing interests.

Additional information

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Correspondence should be addressed to Jonathan Salerno.

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