Navigating the Complexity of Environmental Migration in the Context of Climate Change: Interdisciplinary Reflections on Concepts and Methods

IRD CoSav Migrations, Working paper– April 2026

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Contribution

Lucie Clech (first author) structured the article and its sections, developed the argumentation and wrote the different versions. Sylvie Fanchette (last author) secured the funding, organised and co-animated the workshop with Fabien Durand (second-to-last author), and provided critical input throughout the development of the article and its various versions.

Co-authors, listed in alphabetical order, reviewed and commented on their respective section, and contributed to the refinement of their case study description: Kees van der Geest, Jamal Khan and Fabien Durand contributed to Part 2 on Hazards, Bishawjit Mallick on Part 3 on Livelihoods, Marion Borderon and Coline Garcia contributed to Part 4 on habitability, Kevin Chapuis contributed to Part 5 on agent based modelling and Flore Gubert and Anne-Sophie Robilliard contributed to Part 5 on econometrics tools. All authors have agreed and read the full manuscript and contributed to the final adjustments.

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Abstract

This article, from the perspective of a collective of researchers from the French National Research Institute for Development and collaborators, presents and discusses the conceptual and methodological frameworks they have developed to study environmental migration and (im)mobilities. It is based on a workshop organised within the IRD's CoSav Migrations network, which brought together researchers seeking to better understand how environmental and climatic changes drive, constrain and interact with human migration and (im)mobilities.

This article emerges at a particular moment: a third generation of researchers now works in this field, sharing a growing recognition that environmental migration and (im)mobilities cannot be reduced to simple causal chains. Understanding migration complexity requires approaches that are conceptually grounded, methodologically diverse, and capable of engaging with uncertainty, multi-causality, and scale interactions.

This work arises from a collaborative, interdisciplinary process that brings together researchers from various backgrounds in social and environmental sciences. This diversity necessitated ongoing dialogue to clarify the underlying epistemologies, temporalities, scales and analytical priorities of concepts still under development. Instead of suggesting a single unified framework, the article describes an evolving field in the making, rooted in empirical realities and shaped by ongoing discussions. In doing so, it emphasises the importance of conceptual reflexivity, methodological diversity, and collaborative knowledge production to address a research object that remains unstable and context-dependent.

The article is organised around four interconnected dimensions of this complexity. Chapter 2 investigates environmental hazards, highlighting their compound, non-linear, and multi-scalar characteristics. Chapter 3 focuses on livelihoods, understood as socially and historically rooted practices that shape migration and staying strategies. Chapter 4 presents habitability as an inclusive concept that reflects the relational and political processes through which environments become differently liveable. Finally, Chapter 5 addresses methodological challenges, presenting complex adaptive systems as a comprehensive framework alongside agent-based modelling and the ongoing limitations of data and scale.

Taken together, these contributions highlight an evolving field characterised by conceptual plurality, methodological diversity and the need for deeper dialogue across disciplines and knowledge systems. It calls for research that is more reflexive, integrative and attentive to power relations, local knowledge and cross-scale dynamics in order to better understand the present and future of migration and (im)mobilities in contexts of environmental change.

Key words: environmental migration and mobilities, climate, compound hazard, livelihood, habitability, complex adaptive system, agent-based modelling

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Introduction

§1 Global context

Since the origin of humanity, migrations have shaped the evolution of our species, populations, identities, cultures, and even biology. While our ancestors moved in response to natural fluctuations in their environment and resources, the contemporary situation differs fundamentally. Whether hunter-gatherers, farmers, fishermen, or city dwellers, all populations are now affected by anthropogenic changes that impact our planet, including land and water transformations, biodiversity loss, and climate change (Calvin et al., 2023), often occurring together. As environmental degradation intensifies due to these changes, environmentally driven human migrations and (im)mobilities (see §5 for our terminological justification) have become a growing concern.

Measuring environmental migration is complex. International organisations often focus on migration caused by extreme events, with figures that are striking but incomplete: the Internal Displacement Monitoring Centre (IDMC) documented 26.4 million new displacements due to environmental disasters in 2023 (IDMC, 2024) and 45.8 million in 2024 (IDMC, 2025), surpassing conflict and violence-driven migration. However, these numbers obscure more than they reveal: they do not differentiate among types of movement or indicate when most of the displaced individuals return home. In other words, they reduce complex phenomena to geographic and climatic determinism. The Intergovernmental Panel on Climate Change (IPCC) similarly presents environmental change as a primary driver of human displacement (Calvin et al., 2023; Intergovernmental Panel On Climate Change (IPCC), 2023) and the World Bank projects that over 216 million people could become internal climate-related migrants by 2050 (Clement et al., 2021). These projections, while useful for policy, oversimplify complex issues into a narrow narrative.

The impacts of environment-related migration are profound. Migrant populations often experience loss of livelihoods, cultural dislocation, disruption of social networks, and physical and mental health issues, while host communities may face increased pressure on resources, housing, and infrastructure (Intergovernmental Panel On Climate Change (IPCC), 2023). Environmental degradation can worsen in densely populated areas, heightening socio-ecological tensions. Moreover, the absence of formal status leaves millions without legal protection, access to aid, or lasting solutions. These institutional gaps risk marginalising vulnerable groups and hampering coordinated responses.

However, environmental migration should not be limited to forced displacements alone. For many people whose livelihoods depend on the natural environment, such as nomadic populations, farmers, pastoralists, hunter-gatherers, and fishing communities, movement (from micromobilities to permanent migration) is a vital livelihood strategy and adaptive practice (Black, Bennett, et al., 2011; Scoones, 1998). This is especially true for numerous indigenous populations whose livelihoods rely on close interdependencies with their natural surroundings (Ismail et al., 2026). However, rigid political and legal frameworks can prevent these communities from adjusting their movement patterns beyond areas often limited by dominant authorities, thereby restricting their adaptive capacity. Socio-cultural factors, including social norms, institutions, and governance, interact with environmental factors to shape and constrain adaptive capacity (Huitema et al., 2016; Adger, Dessai, et al., 2009), resulting in a wide variety of migration practices. Additionally, migration does not always serve as an effective adaptive strategy, as people may be forced to stay put, translocal

households may become disconnected from migrants, or migrants may face similar risks in both their places of origin and their destination (Sakdapolrak et al., 2024).

The framing of environmental migration must also consider various forms of non-migration and immobilities, including the right to stay for those who choose to do so, as well as the inability to move due to multiple intersecting factors such as elderly persons, women with care responsibilities, and socially or economically marginalised groups (Black, Adger, et al., 2011) who may rely on invisible mobilities (Garcia et al., 2025). Environmental migration thus covers a spectrum from forced displacement and (mis)adaptive movement to voluntary or involuntary immobilities. Therefore, we must urgently conceptualise environmental mobilities as a complex interaction between environmental, socio-economic, and political factors, with significant implications for population well-being, health, and ethical considerations (IPCC, 2022; Foresight, 2011; Black, Adger, et al., 2011; McMichael et al., 2006).

§2 IRD's Strategic Positioning

The IRD (Institut de Recherche pour le Développement, or French National Research Institute for Sustainable Development in English) positions itself as a key player in advancing climate-related environmental sciences through its missions and expertise. Indeed, the IRD possesses unique assets for studying migration related to environmental and climate change: its commitment to research that supports sustainable development, combined with partnerships across numerous countries in the Global South, provides unique opportunities for both localised case studies and transnational comparative analyses of these emerging migratory phenomena. This strategic position underpins its relevance in developing innovative approaches within this field. Furthermore, issues of environmental migration align closely with the IRD's core commitments (IRD, 2025b). Promoting health equity, conserving ecosystems, fostering social cohesion, and supporting sustainable resource management, each of these institutional priorities directly resonates with the challenges of environmental mobilities in the Global South. This alignment demonstrates that investing in this domain is not merely expanding thematic scope but also fulfilling a strategic and ethical imperative. By allocating institutional resources and steering its research towards environmental migration, the IRD responds to a dual need: establishing itself as a reference actor on a progressively important issue, whilst reaffirming its mission to promote more equitable development in a transforming world.

Firstly, countries in the Global South bear a disproportionate burden of environmental changes whilst contributing minimally to their causes. Smallholder farmers, coastal communities, and marginalised rural and urban populations face increasingly frequent and intense flooding, droughts, cyclones, heatwaves, unpredictable rainfall, air pollution and erratic seasonality patterns. The IRD can generate specific knowledge on how environmental stressors interact with existing socio-economic vulnerabilities to drive out-migration. This research contributes to three of the IRD's fundamental missions: 1- advancing scientific knowledge grounded in local realities; 2- fostering innovation for resilient and sustainable development pathways; and 3- strengthening the capacities of partner institutions in the South through equitable collaboration.

Secondly, methodological complexity strengthens this argument. Environmental human migrations go beyond disciplinary boundaries, requiring integrated approaches that connect the biological and physical sciences with social research, public health, and legal frameworks. More fundamentally, it calls for transdisciplinary collaboration with knowledge

communities, policymakers, and civil society. Since 2020, the IRD's strategic focus on sustainability science, along with its longstanding mandate and experience on sustainable issues, is reflected in this methodological requirement, which highlights systems thinking, reflexivity, and epistemological diversity in addressing global sustainability challenges (French National Research Institute for Sustainable Development, 2023a, 2023b, 2024). In direct response to this orientation, the IRD created the COSAVs in 2021 (IRD knowledge communities or *communautés de savoir de l'IRD*) (IRD, 2025a): interdisciplinary and transdisciplinary working groups aimed at fostering collaboration between researchers, partners, and societal stakeholders. These communities specifically seek to promote conceptual and methodological discussions that are essential to a more open, collaborative, and sustainable research approach.

§3 The problem of oversimplification

Given the IRD's interdisciplinary mandate and its partnerships in the Global South, there is both an institutional and an epistemic imperative for its scientists to engage with research on environmental human migration. A growing body of literature has shown that the dominant, single-narrative framing of climate change as a direct driver of large-scale migration is a reductionist view of the realities of human mobilities and requires nuance that is important for policy-making (Piguet et al., 2011). Along these lines, the foresight report warned against deterministic interpretations and highlighted the multi-causal, context-dependent nature of climate migration (Foresight, 2011). Nearly a decade later, this warning is reiterated, as more recent research continues to document the heterogeneous and multicausal nature of environmental migration (Cattaneo et al., 2019) and the risk of oversimplified framings persisting. As (Boas et al., 2019) argue, prevailing narratives of climate-driven mass migration ("the climate migration myths") fuel oversimplified policy responses and obscure the empirical complexity of migration, leading to unintended consequences. Contextual specificity, local experiences and knowledge, and bottom-up approaches are especially important in understanding local complexity, livelihoods, and (un)habitability (Boas et al., 2019, 2025).

§4 Complexity of the interactions

This call for multi-causal, context-sensitive approaches is especially relevant given the heterogeneity of environmental changes involved. Environmental drivers of migration are not limited to single, extreme events; they encompass a wide range of interconnected phenomena, from sudden disasters such as floods and cyclones to slow-onset processes such as drought, coastal erosion, salinisation, and rising temperatures and sea levels (Khan et al., 2025; AghaKouchak et al., 2020; Zscheischler et al., 2018). These changes often occur simultaneously or in succession, and their impacts accumulate and interact over time. They also intersect with structural vulnerabilities, such as land degradation, poverty, and limited access to essential services, which worsen exposure and diminish adaptive capacity. Responses to environmental changes are therefore highly varied. Instead of a straightforward movement from "vulnerable" to "safe" areas, migration patterns are often fragmented, temporary, seasonal, aspirational, or circular. In many cases, migration is not a sign of failure but a conscious strategy, migrants making the best of a difficult situation. However, this may create new vulnerabilities (Schwerdtle et al., 2021), especially in overcrowded urban areas or environmentally fragile host regions.

Complicating matters further, these processes create feedback loops: increased settlement density can strain natural resources, contribute to localised environmental degradation, expose people to new types of physical or mental illnesses, or heighten socio-political tensions, all of which can trigger new forms of mobilities. The dynamic interaction between environmental change and migration emphasises the need for research that captures complexity.

The IRD, with its interdisciplinary expertise and longstanding partnerships in the Global South, is specially positioned to address this complexity. By combining diverse methods and knowledge, its researchers can help develop robust, practical frameworks that mirror real-world conditions and promote inclusive, sustainable solutions.

§5 Pluralism of concepts and the resulting conceptual complexity

Migration studies have been shaped by a diverse, yet fragmented, range of disciplinary perspectives within the social sciences (De Haas, 2021; Massey et al., 1993). Anthropology, economics, geography, history, political science, sociology, development and sustainability sciences each offer distinct methodological and analytical lenses that, while different in approach, tend to complement rather than contradict one another, but also pose challenges for coherence and methodological integration (De Haas, 2021).

Early migration studies (De Haas, 2021; Massey et al., 1993) were dominated by several co-existing theories. Neo-classical migration theory, views migration as an outcome of rational individual decision-making aimed at maximising income or utilities (Sjaastad, 1962). The new economics of migration reconceptualises migration as a household strategy for managing risks and overcoming market failures (Stark, 1991). In contrast to these individual approaches, structural approaches, drawing on neo-Marxist political economy, emerged to address structural inequalities. The dual labour market theory (Piore, 1979), influenced by institutional economics, focuses on the structural demand for migrant workers in advanced economies. The World System Theory (Wallerstein, 1974) emphasises how global capitalist structures generate mobilities from peripheral to core regions. Those structuralist approaches have been criticised for overlooking individual agency (De Haas, 2021).

The widely used push-pull framework (Lee, 1966) identifies environmental degradation as a "push" factor and better conditions elsewhere as "pull" factors. However, it has been criticised for oversimplifying and failing to capture the dynamics of decision-making (De Haas, 2021; Van Hear et al., 2018).

The Foresight report (Foresight, 2011) incorporates uncertainty and future risk, aligning with anticipatory governance, yet faces challenges in empirical application. More recent models, such as the aspirations and capabilities framework (De Haas, 2021), consider both individuals' desires to migrate and their capacity to do so, offering greater nuances.

Compared to other migration studies, environmental migration studies face an additional layer of complexity stemming from the need for interdisciplinary approaches that integrate environmental and biophysical sciences with social and human sciences. Collaboration across those scientific disciplines remains marginal. While some social scientists criticise social-ecological studies that overlook context, social dynamics, and power structures, other social scientists note that, too often, physical and biological dimensions are missing from social studies (United Nations Environment Programme, 2023). Many studies either reduce environmental complexity to a single proxy within social science frameworks, lacking a deeper understanding of bio-physical processes, or focus primarily on bio-physical

dynamics while neglecting the intricacies of social mechanisms. This disciplinary divide illustrates the limitations of siloed research and underscores the need for integrative approaches that embrace complexity across disciplines.

To address different topics at the intersection of society and the natural environment (such as conservation, natural resource use, and land management), a wide array of frameworks has adopted interdisciplinary approaches with a social-ecological perspective (Binder et al., 2013) that share similar challenges. For environmental mobilities, several frameworks can work synergistically with established concepts and approaches, for example, ecosystem services can align with the vulnerability framework (United Nations Environment Programme, 2023), livelihood (Clech et al., 2024; Mallick, 2019) or with habitability approaches (Sterly, Borderon, Sakdapolrak, et al., 2025). Yet critics observe that, despite their "socio-ecological" branding, many social-ecological studies often privilege ecological perspectives over social ones, creating an analytical hierarchy that contradicts their integrative aspirations. Rather than transcending oversimplification, they merely relocate it within a more complex theoretical construction. Finally, by focusing on ecological context, other dimensions and scales are missed. Daoust et al (Daoust & Selby, 2024) speak about climate and environmental change as a "global socio-ecological and not just an environmental problem".

Along the same lines regarding the inclusion of the socio-political dimension, and driven by the imperative to reflect realistic conditions, multi-exposure approaches are increasingly gaining attention, encompassing both compound events and multi-crisis contexts. Sultana (Sultana, 2021) has pointed out the importance of not addressing climate change alone but considering multiple crises overlapping, while other scholars have conceptualised the term polycrisis (Dinan et al., 2024; Lawrence et al., 2022, 2024) "as the causal entanglements of crises in multiple global systems" and discussed the critics and limitations of the concept (Delannoy et al., 2025; Lawrence et al., 2024). Beyond their compound nature, crises are also politically constructed and strategically framed: their classification along dimensions of time, space and intentionality is itself a strategic act with significant implications for institutional responses, as illustrated by the "crisis cube" concept (Profeti & Toth, 2026).

The tendency to overlook the socio-political dimensions is a constant concern, even for new conceptualisation. Recent work by Boas et al. (2025) warns against the risk of overemphasising physical factors in defining uninhabitability at the expense of integrating local experiences and knowledge. They argue that community perceptions of environmental "habitability" often diverge significantly from external scientific evaluations imposed upon these populations.

Recognising this limitation, (Daoust & Selby, 2024) present an alternative framework based on a multiple-pathways approach that deliberately weaves together insights from different theoretical traditions, seeking to achieve the balanced integration that socio-ecological frameworks promised but failed to deliver. In their new framework, they included five different pathways: short-term shocks, long-term climatic and related changes, environmental "pull" factors, climate adaptation and mitigation measures, and perceptions and narratives (Daoust & Selby, 2024). However, integration of such complexity at national and transnational levels presents significant challenges, particularly in the context of inferential statistics and demographic projections.

Finally, the disciplinary plurality also manifests at the level of terminology. We use the pairing migration and (im)mobilities as our preferred formulation throughout and treat

migrations, mobilities, and movements as broadly interchangeable in a pragmatic way to avoid repetition, as with immobilities and non-migration. However, the two terms carry different theoretical legacies and political valences, and we want to clarify our positionality.

In the mobilities turn literature (Boas et al., 2022; Cresswell, 2016; Faist, 2013; Sheller & Urry, 2006), mobilities function as the broader umbrella concept, encompassing all forms of movement, daily, seasonal, circular, long distance, transnational, translocal, as well as their absence. Within this framework, migration is one category among many, defining longer distance or durable displacement. The mobilities approach decentres the figure of "the migrant", a category that can be politically charged and analytically reifying.

Both external and internal critics of the movement have pointed out the risk of depoliticisation of the mobilities concept (Cresswell, 2016; Glick Schiller & Salazar, 2013). We are attentive to this critique. Several co-authors are grounded in migration studies, a field whose analytical strength lies in keeping both the person who moves (the migrant) and the sociopolitical conditions of that movement in view, including the power asymmetries that constrain some movements more than others. The concept of migration also carries traction in official discourse and policy, where it simultaneously names a process, a subject and a set of rights.

Our formulation, environmental migration and (im)mobilities, is intended to hold this tension rather than resolve it. We position ourselves primarily within the migration studies tradition, while extending our analytical scope to the full spectrum of movements and non-movements encompassed by the mobilities framework, with particular attention to the political nature of movements and the asymmetrical power relations that structure it. The pairing thus signals both our disciplinary anchoring and our intention to capture the full spectrum of human movements and their absence. However, further discussion will be needed on terminology, as this pairing remains imperfect.

We opted for environmental over climatic for several reasons: climate is part of the broader environment; multiple environmental hazards may interact and compound one another (see Part 1); the causal chain linking climate to the ecosystem is often indirect and non-linear; climate is not always the most significant driver of environmental change. Finally, terminology within each case study reflects the choices of its respective author.

§6 A need for new reflection on conceptualisation

This conceptual plurality has enriched debate, and also reveals a lack of convergence. The complexity of environmental migration and (im)mobilities calls for a pluralistic, integrative approach, one that bridges structural dimensions and individual agency, embraces multi-scalar analysis, and is capable of engaging with uncertainty and change.

There is thus a pressing need for a truly interdisciplinary conceptual dialogue that fosters meaningful exchange between the social sciences and the physical and biological sciences. Such integration can also be transdisciplinary, actively involving local populations, civil society and local institutions as co-producers of knowledge to ensure that research is context-sensitive, socially relevant, and ethically grounded. For this aim, inter- and trans-disciplinary discussions are needed to foster new conceptual and methodological thinking.

This article responds directly to the IRD's call for the development of sustainability science within the institute. It compiles the results of a workshop organised by COSAV Migrations, which spearheaded this writing initiative, and establishes links with COSAV Climat-Sciences-Sociétés and other COSAV-like Biodiversité by documenting a (non-

exhaustive) variety of approaches used by IRD researchers or IRD collaborators to initiate and foster a collective conceptual and methodological reflection.

The article unfolds into five sections: Chapter one on the workshop aims and methodology, Chapter 2 on compound hazards, Chapter 3 on Livelihood, Chapter 4 on habitability and Chapter 5 on methodological challenges to study environmental migration, with a first section on complex adaptive systems and agent-based modelling, and a second section on econometrics tools and data. Chapters 2, 3, and 4 aim to define the concepts, present case studies and lessons learned (from the co-authors), and follow with an interdisciplinary dialogue and a reflexive discussion emerging from a World Café methodology.

Part 1 - Workshop Aims and Methodology

Ethical statement

This paper is the product of a collective work, based on a workshop. All co-authors were participants in the workshop and consented to the publication of this work.
All case studies have been described in peer-reviewed papers and have received ethical clearance.

Context

A working group on environmental migration induced by environmental and climate degradation (IDEC) has been created within the CoSav Migrations network of the IRD (CoSav: IRD knowledge communities or *communautés de savoir de l'IRD*). This group is bringing together about 20 academics and PhD students from diverse academic backgrounds in France and abroad who work in the global South. The group monitors research projects, publications, calls for proposals, and conferences on environmental migration. Its shared bibliography informs discussions on concepts and methodologies.

The working group emphasises several key priorities: conducting empirical local and regional studies since most environmentally induced migrations are internal or local (IDMC, 2024), mobilising concepts such as "livelihoods" and territorial "habitability" in an increasingly uncertain world and developing new models of mobilities/immobilities, migration/non-migration, involuntary displacements, and translocal livelihoods (across multiple sites, genders, social classes and cultures) especially in risk hotspots (deltas, coasts, islands and arid regions). This group also aims to foster genuine interdisciplinarity between the social and human sciences and the environmental and physical sciences. It also aims to increase its visibility as an interdisciplinary network, to engage new researchers and to support a new generation of interdisciplinary researchers.

Workshop organisation

The "Concept, Theories, and methodologies for addressing environmental Migration" was organised by Sylvie Fanchette and Fabien Durand, from the IDEC working group and for the IRD's COSAV "Migration" on the 7 and 8th of November 2024 at the Université de Paris, Bâtiment Olympe de Gouges, Place Paul Ricœur 75013 Paris. For this two-day event, about 20 people attended, including PhD students, postdocs and senior researchers from the IRD or collaborating organisations. The workshop program is available in the appendix.

The first day was a plenary session, organised around several conceptual or methodological themes: Hazards, Habitability, Complex Systems Approach, Livelihood, and Agent-Based Modelling. The "Hazards" session included two presentations, the first one being about Compound Flooding: A Key Concept for Understanding Coastal Hazards from Jamal Khan at the IRD/LEGOS (France) and the second one about the project "Where the rains fall: methods and findings" from Kees Van Der Gerst at the UN University Bonn (Germany). The habitability session included three presentations, a two-in-one: one on the concept and one on a case study in Kersa, Ethiopia, as an illustration of "Rethinking habitability for an unequal and connected world," by Marion Borderon and Coline Garcia at the University of Vienna, Austria. The third presentation covered the questions of

quantitative data and data use: "Economic tools to study environmental migration" from Anne-Sophie Robilliard and Flore Gubert at the IRD/Creda (France). The session on the complex systems approach was illustrated by a presentation, "Exploring the Climate Change Migration Nexus: A Complex Systems Approach in Southwest Bangladesh," by Lucie Clech, a post-doc at Ceped/IRD (France), which also drew on a livelihoods approach. The session on the "Livelihood approach: Intergenerational learning as a crucial mechanism for communities to adapt" was presented by Bishawjit Mallick, an Associate Professor in Climate Change and International Development Studies at Utrecht University (Netherlands). Finally, the session on agent-based modelling focused on a presentation by Kevin Chapuis at the IRD (France) titled "Agent-based modelling principles (Gama platform): evacuation model in case of catastrophic event." Each presentation included one or several case studies that were already published or are ongoing projects.

The second day was reorganised on the spot using the world café methodology (Löhr et al., 2020) in the same location. Three round tables were organised, each focusing on one of the three core concepts (hazards, livelihood and habitability) to cover both conceptual discussion and methodological discussion for the operationalisation of each concept. Complex-systems approaches and agent-based modelling were included in the livelihood roundtable. Workshop participants rotated among the table concepts, discussing each for 30 minutes in groups. This world café session was followed by a group feedback session.

Manuscript structure

Environmental migration research draws upon a diverse array of concepts, approaches and methodological tools. As a research collective comprising early-career and established researchers from different disciplinary backgrounds across the social and physical sciences, from both the IRD and partner organisations, we present here a non-exhaustive overview of the frameworks and methods employed in our recent work.

For this manuscript, two choices were made: to use migration and (im)mobilities to encompass all environmental movements and different timeframes, from short-term mobilities (e.g., evacuation in preparation for an environmental disaster) to permanent migration. However, we are well aware that we covered only a fraction of the identified migration spectrum because we focused on the concepts, methodologies, and objects studied by the workshop participants. Several other important perspectives lie beyond its scope, including climate (in)justice, triple-nexus approaches linking migration with conflict or health, and climate change, the analysis of compound and cascading risks, and the migration–sustainability nexus. Likewise, forced displacement, whether driven by conflict or by state and private development projects such as dam construction, mining, or large-scale agriculture, was not examined directly, although it raises particularly important and sensitive issues. We also decided to reorganise the order of themes and to restructure our paper as follows: a first part on methodology and the paper's objectives; a second part on hazards; a third part on livelihoods; a fourth part on habitability; and a part chapter on methodological challenges in studying environmental migration. The second through fifth parts were based on the plenary discussions of the concept, supplemented with updated literature, and illustrated with case studies, followed by a description of the collective discussions that were initiated during the World Café session and continued throughout the manuscript writing process.

The compound hazard concept (Part 2) is presented through the "Where the rains fall" multi-site project (Guatemala, Peru, Ghana, Tanzania, Bangladesh, India, Thailand,

Vietnam), followed by a compound-hazard approach in Madagascar to highlight the growing complexity from a physical perspective. Livelihood (Part 3) is illustrated through several rural studies in Bangladesh: one on non-migration and the other on the intergenerational dimension. The habitability concept (Part 4) is presented through a project in Ethiopia. The methodological chapter (Part 5) introduces, in a first section, the challenge of integrating concepts through the example of complex adaptive systems (one study in Bangladesh) and agent-based modelling, and in a second section, the methodological challenges of data availability and data use (three case studies, two in Senegal, one in Mali).

Part 2 - Hazards in environmental migration and (im)mobilities studies

Conceptual foundations

Environmental hazards drive human migration, shaping mobilities decisions through their direct and indirect physical impacts and the socio-economic disruptions they cause. Pathways from hazards to migration might be simple or complex, direct or indirect and include feedback loops. Understanding the distinction between hazards and risks is fundamental to analysing environmental mobilities. The UN Office for Disaster Risk Reduction (UNDRR) Sendai Framework Terminology (2017) defines hazard as "a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation" (United Nations Office for Disaster Risk Reduction (UNDRR), 2017b), essentially the potential source of harm. Disaster risk, by contrast, is defined by UNDRR as "the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity" (United Nations Office for Disaster Risk Reduction (UNDRR), 2017a). In this context, risk represents the likelihood of negative outcomes affecting people, systems, or assets, calculated from the combined effects of hazards, exposed assets or populations, and the vulnerability of those elements.

Environmental hazards are extreme events or processes that can put human well-being and resources at risk. We distinguish three broad types of environmental hazards: natural hazards; hazards shaped by hydraulic, urban, or territorial development; and hazards whose frequency or intensity will increase with climate change. Significant challenges persist in measuring hazards and attributing impacts. This complexity underscores the analytical challenges in environmental migration research and warns against oversimplified interpretations that explain migration solely through climate change, which leads to an over-climatisation of the environmental question.

These hazards may occur as single-driver events, isolated droughts or floods, or as compound events (Zscheischler et al., 2020, 2018), in which multiple hazards interact simultaneously or consecutively. The Intergovernmental Panel on Climate Change (IPCC, 2021) characterises compound events as situations involving multiple climatic drivers and/or hazards that contribute to societal or environmental risk. IPCC definitions encompass: 1- events where multiple extreme events of similar or different types occur simultaneously and/or successively; 2- combinations of extreme events with underlying conditions (such as vulnerability and service access inequality) that amplify their impact; and 3- combinations of events that are not themselves extreme but lead to extreme outcomes when combined. Traditional risk assessment methods typically examine only one hazard at a time or several hazards separately, without accounting for complex hazard interactions, potentially underestimating or overestimating risk.

These definitions highlight the complexity of the relationships between hazards and migrations, moving beyond simple, linear cause-and-effect models toward a better understanding of multifaceted, non-linear interactions among multiple environmental

stressors and human responses. In this context, (im)mobilities becomes both a response to environmental risk and a risk management strategy, even if unsuccessful.

Case study 1: Where the Rain Falls" project

The project "Where the Rain Falls" (2011-2013) investigated the intersections between rainfall variability, food and livelihood security, and migration across diverse global contexts (Afifi et al., 2016; Warner & Afifi, 2014). The conceptual framework integrated rainfall variability, food security, and migration through the lenses of household vulnerability and resilience. Key concepts included "content migration" (adaptive) versus "erosive migration" (survival-driven), addressing the central question: under what circumstances do households use migration as a risk management strategy when facing rainfall variability and food insecurity?

Methodology: The study employed a comprehensive mixed-methods approach spanning eight countries (Guatemala, Peru, Ghana, Tanzania, Bangladesh, India, Thailand, Vietnam) that represent diverse ecosystems and socio-economic contexts. The research methods included household surveys (N=1300), participatory rural appraisal (PRA), expert interviews, secondary data analysis including rainfall data to cover droughts, floods, dry spells, and changing seasonal patterns, and agent-based modelling (Afifi et al., 2016; Warner & Afifi, 2014; Rademacher-Schulz et al., 2012). PRA tools such as mobilities maps, event histories, seasonal calendars, and livelihood risk rankings were aimed at capturing local perceptions and strategies.

Findings revealed the direct impacts of rainfall variability on agricultural production and household income, driving context-dependent migration decisions. Migration prevalence was higher among households dependent on rain-fed agriculture with limited livelihood diversification, suggesting that different livelihoods are not impacted in the same way or through the same pathways. Crucially, resilient households utilised migration to enhance adaptive capacity, while vulnerable households relied on migration as a survival strategy, often exacerbating their vulnerability. Some households remained "trapped," meaning they were unable to migrate due to insufficient resources, highlighting immobilities as a critical dimension of mobilities (Afifi et al., 2016). The project identified four distinct household profiles: resilient households, households surviving but not flourishing, households relying on erosive coping strategies, and trapped populations (Warner & Afifi, 2014).

Debates, limitations and lessons learned: The project contributed to ongoing debates about migration as a positive climate adaptation versus as an indicator of adaptation limits and constraints. It highlighted the dynamic interplay between resilience and vulnerability in migration decisions, challenging binary conceptualisations of adaptation. However, limitations included geographic scope restricted to eight countries and potential bias from self-reported data. Lastly, agent-based modelling was applied only in Tanzania (Smith, 2014), which limits the generalisability of this methodological approach (see Chapter 5 for agent-based modelling). The project's strength lay in systematic cross-country comparisons that provided empirical evidence for policy development, with the integration of qualitative and quantitative methods enhancing the robustness of the findings. Finally, this project paved the way for new research orientations that broadened the scope from examining the causes of migration to analysing both the impacts and outcomes of migration.

After the Rainfalls Project, UNU-EHS research focused on developing a multidimensional vulnerability index that could be quantitatively linked to different livelihood and migration patterns (Van Der Geest & Warner, 2015), and it shifted focus toward optimising migration

policies (Mombauer et al., 2023), and from "climate migration" to "human mobilities in the context of climate change", including migration, displacement, planned relocation, and immobilities (Link et al., 2025; Oakes et al., 2022; Thalheimer et al., 2021). Furthermore, UNU-EHS research has started paying more attention to people's perceptions and attitudes, subjective norms (using Q-methodology), voluntary and involuntary immobilities, and qualitative storytelling, including biographical migration and livelihood histories (Ayeb-Karlsson, 2020; Oakes, 2019; Van der Geest et al., 2019).

Case study 2: Compound flooding: understanding multi-driver hazard systems

As a part of the Belmont Forum CHAIN project (2023-2026), which aims to better understand the human migration in Madagascar driven by climatic factors, such as drought and flood, directly or indirectly. Tropical cyclones are a major environmental hazard in Madagascar, but their role varies across the country. On one hand, flooding is a major consequence of these extreme weather events, which impacts agriculture, destroys housing, schools, and other infrastructure, and consequently disrupts the economy. On the other hand, in drought-prone regions, particularly in southern Madagascar, rainfall associated with cyclones often plays an important role in overall water availability for irrigation. This study from (Khan et al., 2025), focuses on the flooding and demonstrates for the first time that the flooding in Madagascar is inherently compound, with significant contributions from both oceanic factors (i.e. storm surge, tide, wave setup) and continental factors (i.e. rainfall, runoff) that interact non-linearly. Their compound flood modelling approach provides an understanding of the flooding hazard that aligns with local perceptions of this hazard. The affected population can experience several flooding episodes in sequence, some predominantly driven by oceanic factors and other by continental factors. This demonstrates that consideration of compound flooding is crucial for effective communication and disaster preparedness.

Compound flooding (Khan et al., 2025) represents a paradigm shift from single-driver flood models towards understanding the cascading effect of complex multi-hazard interactions. The concept integrates oceanic factors (storm surges, tides, wave setup) with continental factors (rainfall, river discharge) to assess cumulative flood impacts. This approach builds upon established hazard research by introducing sophisticated physical modelling capabilities that capture non-linear physical interactions between land and oceanic processes. In addition to capturing the flooding event holistically, their modelling capability approaches the household scale (30m), which represents another important advancement in assessing flooding risk at fine resolution (Khan et al., 2025).

Methodology: The study (Khan et al., 2025) employed a sophisticated ocean-continent coupled modelling framework of the hydrodynamics, using ocean-waves coupled hydrodynamics modelling for oceanic processes and continental runoff modelling for land hydrology and flooding. They have developed a high-resolution multi-source bathymetric dataset (30-metre resolution inland) as well as atmospheric forcing (wind and pressure) representing a significant technological advancement over an acutely data-scarce region. Rigorous validation was conducted using remote sensing data, including flood frequency, flood maps, and altimetry-derived water levels, achieving good realism in the modelled flood extent. This methodology demonstrates a substantial increase in complexity over social science approaches, requiring advanced computational resources and interdisciplinary expertise spanning hydrology, oceanography, and climate science.

Findings revealed the complexity of compound flooding during Tropical Cyclone Batsirai. Oceanic contributions extended up to 10 kilometres inland along rivers, while rainfall-runoff

dominated inland flooding. Their results clearly expose the limitations of the typical flood modelling approach: only storm-surge modelling would have completely failed to capture the large-scale inland flooding, while only hydrologic modelling would have vastly underestimated the coastal flooding. Most significantly, non-linear interactions between oceanic and continental factors reduced total water levels by up to 30% for this case study, challenging additive flood-risk assumptions and demonstrating that physical system complexity far exceeds simpler linear hazard models. Interviews revealed that residents noticed flood peaks, with oceanic storm surge peaking 18 hours before maximum riverine discharge, resulting in consecutive flooding events that prolonged hazard duration. Agricultural impacts were substantial, with 30% of flooded areas classified as vegetation and 27% as croplands, highlighting socio-economic exposure through advanced spatial analysis.
Debates, limitations and lessons learned: The study challenges traditional single-driver approaches by demonstrating the importance of compound interactions, though questions remain about the variability of non-linear dynamic interactions across events. Significant technical limitations included data scarcity, particularly so for observational water levels, as well as the resolution and accuracy of the land topography. Wave run-up processes remained unresolved due to computational constraints, and assumptions about atmospheric forcing introduced uncertainties. The one-way coupling approach between oceanic and continental models may have overlooked additional dynamic feedbacks, and focusing on the Mananjary Basin (Eastern Madagascar) limited its broader applicability. Despite limitations, the research demonstrates substantial methodological strengths through advanced integrated modelling and high-resolution validation based on remote-sensing dataset making it scalable and transferable. The scalable framework is applicable to other cyclone-prone regions globally, with emerging needs including global-scale compound flood modelling and future climate change impact studies incorporating sea-level rise and intensified cyclones. Beyond these challenges in environmental sciences, a key aspect is the need for a match between the scales resolved when assessing hazards and those required by existing socio-economic databases. Typically, existing national censuses are too coarse-grained (spatially) and infrequent to jointly and quantitatively analyse hazard, vulnerability, and exposure across the Global South. Dedicated household surveys appear unavoidable; however, they are costly and cannot cover broad regions. High-resolution remote sensing of key socio-economic proxies such as land use, land cover, or night-time lights from spaceborne imagery appears to be a promising way to partially address the lack of global coverage of socio-economic databases at fine granularity.

Synthesis on hazards

Both case studies (Afifi et al., 2016; Warner & Afifi, 2014; Khan et al., 2025) employ different methods to examine how environmental hazards influence migration decisions. The "Where the Rain Falls" project uses rainfall variability, being measured as hazards including droughts, floods, dry spells, and changing seasonal patterns, without considering interactions between hazards and employs established social science mixed methods across multiple sites to understand human responses. The compound flooding study uses advanced Earth system modelling, integrating interactions between oceanic and continental hazards at high resolution, to understand physical hazard processes. Both studies recognise non-linear interactions that challenge simple cause-and-effect relationships and reflect the increased complexity of physical parameters that have been acknowledged over the past decade. Key lessons learned include the complexity of hazards requiring interdisciplinary

approaches, the importance of timing in human responses and physical processes (i.e seasonality), and the recognition that environmental vulnerability varies significantly across contexts and scales. Both studies highlight distinct yet related data challenges: self-reporting biases in migration research versus observational limitations in compound flood modelling. Emerging conceptual challenges include integrating physical hazard modelling with social vulnerability assessments, understanding nonlinear interactions across scales and developing complex frameworks for environmental-social systems. Future research should develop integrated frameworks that combine physical hazard modelling with social vulnerability analysis, while addressing methodological limitations through emerging technologies, new datasets, and expanded geographic applications (Oakes et al., 2023).

Collective reflection from the World Café

Inputs from the World Café session cover several dimensions of hazards by attempting to answer the following question: 1- How does your conceptual framework use environmental hazards? 2- How are hazards selected? 3- How are issues of scale and quality of the variables resolved by the available dataset? Workshop participants have identified various hazards (e.g., rainfall variability, extreme rainfall, flooding, waterlogging, and sea-level rise). Those hazards, used as a proxy for environmental change, might be, but not necessarily, the first in the cascade of events, i.e. seasonality patterns versus flooding, which is often caused by land and water mismanagement and worsened by rainfall, sea-level rise, etc.

Often, the selection and measurement of hazard data (i.e.; reported data from households, measured data from forecast stations, estimated from modelling of satellite data) was restricted by the relevance of the context, some level of subjectivity with the researcher expertise, confidence or network, the data availability, the data quality and the scale accuracy, leading possibly to a choice by default. The research question and the methodology are indeed associated with the scale. Hazard selection and the temporal and spatial scales will differ at the macro level when examining population or system change, compared with the micro level when examining individual migratory dynamics. The question of reliability, suggesting a systematic assessment of the environmental data used (i.e., control of consistency of satellite rainfall data with meteorological station data at the spatio-temporal scales of interest, reported survey data with meteorological or satellite data), might be pertinent, as every context is different and biases and observational errors are ubiquitous, highlighting the need for FAIR data (Findable, Accessible, Interoperable, Reusable). Also, recall is challenging on its own. At least two types of biased perceptions should be considered: 1) faulty memory recall; 2) individuals and communities experiencing events in ways different from anticipated (Ready & Collings, 2021; Ready, 2020). Both cases require further understanding of the socio-psycho-cultural mechanisms that lead to poor or unexpected recall, as perceptions shape behaviours.

Interdisciplinary collaboration, grounded in disciplinary expertise, is essential for making informed choices when selecting datasets and processing variables, whether for physical or social data (see Part 5 for more insights on this point). In the example of compound flooding in Madagascar, the design of the modelling resolution for flooding exposure was guided by both the need for social science (household-scale) and the requirements of representing physical processes, given the dataset's limitations and computational constraints, demonstrating a new frontier for interdisciplinary collaborations. At the same time, the vast volume of information generated by these new generations of physical

modelling and remote sensing poses new technical challenges. More interdisciplinary considerations should be given to compound hazards (IPCC SREX 2012), combining physical, biological and socio-political-economical hazards (context of polycrisis, for example), and how their dynamics can be measured and understood. Finally, the discussion turned to possible solutions to some challenging questions, including the development of datasets that aggregate diverse physical data sources.

Part 3 - Livelihoods in environmental migration and (im)mobilities studies

Conceptual foundations

As Scoones observed (Scoones, 2009): "livelihoods perspectives start with how different people in different places live", and various definitions have been used. Building from early XXth geographical and anthropological studies of human-environment interactions (see (Scoones, 2009) and (Sakdapolrak, 2014) for historical references) but "belonging to no discipline in particular" (Scoones, 2009), livelihood thinking evolved as a boundary term through collaborative interdisciplinary and transdisciplinary work in the mid-20th century between academic research and development practices, before being formalised by Robert Chambers and Gordon Conway in 1992 as the "sustainable livelihoods" framework (SLF) (Chambers & Conway, 1992).

Following this, many development agencies began to advocate for and integrate a sustainable livelihood perspective in their agenda (Scoones, 2009). The British Department for International Development (DFID) includes in the livelihood definition "the capabilities, assets (stores, resources, claims and access) and activities required for a means of living" but notes that the concept can be used in many different ways, and that "the full diversity and richness of livelihoods can be understood only by qualitative and participatory analysis at a local level" (DFID, 1999). The United Nations Development Programme (UNDP) developed this definition to include "the activities, entitlements and assets by which people make a living,"(UNDP, 2017).

Sakdapolrak noticed that the concept has shifted away from examining structural forces to focusing on individual actors, which he calls the "mainstream livelihoods research approach" (Sakdapolrak, 2014). In response to this seemingly depoliticisation of the concept, Sakdapolrak observed that researchers have, since the early 2000s, attempted to restore these overlooked dimensions by reintroducing perspectives on inequality drawn from Bourdieu's work.

The livelihood concept differs from other concepts used in environmental migration research. As explained earlier, vulnerability frameworks focus on risk exposure (Adger, 2006; Cutter et al., 2003). At the same time, resilience approaches emphasise recovery capacity and adaptation following disturbances, often focusing on bouncing back to previous states or transforming to new equilibria (Adger, 2000; DFID, 2011; Folke, 2006).

Livelihood analysis, by contrast, covers the full spectrum of ongoing strategies, resources, and capabilities that people employ to sustain themselves over time, capturing both proactive and reactive dimensions of human agency. Finally, livelihood operates on a different temporal scale. While vulnerability and resilience are often considered in response to specific events, livelihood strategies evolve continuously through historical experiences and cultural transmission both within and across generations. Methodologically, livelihood research draws on a range of methods, from household surveys to assess socio-economic status, to qualitative interviews to capture decision-making processes and cultural values, to participatory assessments to understand community-level dynamics, and geographic information systems (GIS) mapping to analyse spatial patterns of resources and risks.

In the following case studies (Mallick et al., 2020; Mallick & Hunter, 2024), Mallick's work illustrates a livelihood approach that shifts the focus from migration to non-migration. Rather than considering staying as a default or constraint, non-migration is examined as a livelihood strategy shaped by individual and household capabilities, aspirations and constraints. This was made possible by contextualising individuals within specific social-ecological systems (SES), while allowing the analysis to move across scales from individual and household strategies to broader environmental and institutional dimensions (Case study 3). This approach highlights how perceptions, access to resources, and adaptations vary across SES and over time. Furthermore, by integrating intergenerational experiences and historical memory of past disasters (case study 4), Mallick further shows that non-migration decisions are socially and temporally embedded rather than purely reactive to environmental stress.

Case study 3: Non-Migration in Bangladesh

This study (Mallick et al., 2020) examined socio-ecological systems (SES) and livelihood resilience in five coastal communities in Bangladesh, focusing on how socio-environmental characteristics, resources and associated livelihood activities influence migration decisions.
Methodology: Using mixed-methods research in five communities, with 200 household interviews, 38 in-depth interviews, and seven group discussions conducted during March-April 2018, researchers investigated communities representing distinct SES types: irrigated agriculture, rain-fed agriculture, mangrove-dependent systems, and saltwater shrimp farming areas. Key variables included livelihood diversification measures, indicators of social network strength, place attachment scales, and assessments of migration aspirations. The research design strategically selected communities based on cyclone exposure gradients and proximity to international borders to capture the varying environmental and political stressors that affect mobilities decisions.
Findings revealed variations in livelihood resilience and migration aspirations across SES. Rain-fed agricultural systems showed higher resilience scores and lower migration intentions, attributed to opportunities for crop diversification, lower environmental vulnerability, and stronger community cohesion. Conversely, saltwater shrimp farming areas exhibited greater vulnerability to cyclones and salinity intrusion, which correlated with higher migration aspirations and actual out-migration rates. Place attachment emerged as a critical mediating factor, with communities demonstrating strong cultural connections to ancestral lands showing reduced propensity to migrate even when facing environmental risks.
Debates, limitations and lessons learned: The study is based on five coastal communities in Bangladesh, which limits the generalisability of the findings but underscores the importance of considering SES to capture contextual heterogeneity. The authors used a livelihood resilience index based on five components from DFID's SL approach, encompassing social, economic, human, institutional, and environmental capitals, which provides a multidimensional perspective. Environmental capital was a significant predictor of migration aspirations, likely because environmental degradation directly undermines livelihoods dependent on natural resources. Other forms of capital were not significant, possibly because most respondents did not aspire to migrate, and seasonal migration supports long-term non-migration.
As the quantitative data were collected from household heads, indicator selection and aggregation choices may offer only a partial view of household dynamics and mask power relations and intra-household inequalities.

Case study 4: Bangladesh, project Home -Historical Grounding of Migration Decisions of People at Environmental Risks

The project HOME addresses the historical grounding of migration decisions of people at environmental risk. This project examines how past environmental events, lived experiences, and collective memory shape contemporary decisions about migration and non-migration. By taking a long-term, historically informed perspective, the project highlights migration as a context-specific and path-dependent process rather than a purely reactive response to current risks. For instance, it focused on intergenerational resilience following the 1970 Bhola cyclone and specifically on how historical memory and knowledge transmission shape contemporary non-migration decisions (Mallick & Hunter, 2024).

Methodology: The empirical study was conducted in Tazumuddin Upazila. This research involved 150 participants across 50 multi-generational households, specifically targeting three generations to understand knowledge transfer processes and changing adaptation perspectives. The methodology emphasised life history interviews, intergenerational dialogue sessions, and narrative analysis of cyclone experiences and recovery strategies.

Findings: Results revealed distinct generational perspectives on environmental risk and adaptation. First-generation survivors emphasised land inheritance and accumulated social capital as fundamental factors in staying, viewing property as irreplaceable family assets linked to identity and historical memory. Second-generation participants highlighted family obligations and community responsibilities, often serving as knowledge brokers between traditional practices and contemporary adaptation needs. Third-generation respondents showed more diverse aspirations, with some expressing migration preferences driven by educational and economic opportunities, while others demonstrated renewed appreciation for local knowledge after failed migration attempts.

Debates, limitations and lessons learned: Non-migration decisions emerged as a central theme, raising questions about whether staying represents adaptive choice or constrained agency. While some participants preferred to remain due to strong livelihood foundations and social support systems, others appeared constrained by limited resources or a lack of viable migration options. This complexity challenges binary interpretations of migration as either adaptive or maladaptive, highlighting the need for nuanced policy approaches. The limitations include a lack of empirical evidence to explain intergenerational processes, mechanisms, and thresholds; a focus on the 1970 Bhola cyclone, which may not reflect the broader historical dimensions of (non)migration; and a lack of representation of socio-economic vulnerabilities. Besides, a key drawback of Mallick & Hunter's theory of intergenerational resilience (Mallick & Hunter, 2024) is that it may overemphasise continuity and adaptive capacity across generations while underplaying structural constraints, such as poverty, power asymmetries, and policy failures, that limit adaptation options. Additionally, the framework risks romanticising resilience and insufficiently accounting for situations in which intergenerational knowledge is eroded or no longer adequate amid accelerating, unprecedented climate change. This framework was improved by the authors with the tethered resilience concept (Mallick et al., 2025).

Synthesis on "Livelihood"

The Bangladesh case studies demonstrate consistency in identifying key factors that influence non-migration decisions, particularly the importance of livelihood diversification, social capital, place attachment and intergenerational knowledge transfer. However,

methodological challenges persist, including reliance on cross-sectional data that fail to capture the dynamic nature of livelihood adaptation over time, and a limited geographic scope that limits generalizability across different environmental and cultural contexts. Though this may or should not be the aim, as migration or non-migration may be context-dependent local phenomena, and careful thought should be given to scaling up.

A key challenge is that current research focuses too much on whether people are resilient, rather than on understanding how resilience develops and changes over time. The integration of intersectional factors such as gender, age, class, ethnicity, and religion remains underdeveloped despite their importance for intrahousehold and intra-community resource access and empowerment, as demonstrated by ethnographic work. The roles of technological innovations, early warning systems and climate-resilient practices also require greater attention.

This research suggests that governments should support people who want to stay by creating better local opportunities, improving local livelihoods, enhancing community cohesion, and recognising cultural connections to place. Methodologically, future research should prioritise longitudinal studies of livelihood changes over extended periods, comparative analyses across diverse socio-ecological contexts and mixed-methods approaches that balance qualitative depths and statistical rigours. The focus on how knowledge and experiences are passed from parents to children reveals new ways to understand why people choose to stay, which can help improve both research and policies.

Collective reflection from the World Café

The workshop participants have identified several key advantages of livelihood approaches to environmental migration and (im)mobilities. By focusing on livelihoods alongside (social, economic, health, environmental) vulnerabilities, researchers can develop typologies of similar livelihood needs and environmental interactions (e.g., pastoralists versus farmers, and poor pastoralists versus rich ones). This typology enables a nuanced understanding of different livelihood pathways within the climate-ecosystem/agrosystem-migration nexus. Longitudinal approaches are essential for tracking livelihood transformations over time, for example, by identifying when diversification strategies fail and trigger migration. It also provides valuable insights into post-migration outcomes (i.e., upward or downward social mobility for individuals and their descendants), highlighting the possible transgenerational impacts of migration. Key methodological tools include surveys, census data, and multidimensional indices of poverty, vulnerability and related indicators.

Despite these advantages, challenges remain in capturing non-extreme events and short-term environmental changes that traditional data collection may miss. Workshop participants noted that a critical challenge of the livelihood approach is balancing depth and representativeness in data collection. Researchers must strategically select communities for study while considering the comparability of findings across different typologies. For example, agricultural farmers could be compared to other agricultural farmers, but how do you compare farmers to pastoralists? Focus groups present particular dilemmas regarding the balance between participant quantity versus quality of insights, with risks of over- or under-representation of certain groups. The construction of livelihood typologies requires careful consideration of social-ecological systems at community and societal scales. Attachment to longstanding farming and herding practices can deepen the challenge of tethered resilience in balancing rootedness and mobility (Mallick et al., 2025), as cultural and livelihood ties to land and livestock may make households less willing or able to relocate even

when environmental risks escalate. This attachment intersects with the concept's emphasis on cultural values and the presence or absence of opportunities to blend ancestral practices with innovation. When traditional agricultural identities are strong, adapting may require more than biophysical coping can provide; it can constrain flexible, future-oriented decision-making under climate stress. Developing appropriate indicators is essential for measuring livelihoods while maintaining both analytical depth and generalisation of results across diverse contexts and other livelihood types.

Finally, complex adaptive systems (Chapter 5) offer a valuable approach for integrating multiple concepts and allow understanding of, for example, livelihood pathway designs, their interactions, and system's feedback loops. Agent-based models (ABM) (Chapter 5) can provide insights into individual decision-making processes under uncertainty, where populations cannot predict future environmental and economic conditions, locally and at the destination.

Part 4 - Habitability in environmental migration and (im)mobilities studies

Conceptual foundations

The concept of habitability can be traced back to earlier geographical reflections on the idea of a habitable world and on the historical relationship between human societies and environmental livability, notably in the work of Clarence Glacken (Glacken, 1956). Yet in environmental change and migration research, the concept was often mobilised in a much narrower way, primarily to signal biophysical decline and threshold-based forms of environmental stress. Jacobson's characterisation of environmental refugees as a "yardstick of habitability" (Jacobson, 1988) is emblematic of this perspective. More recent scholarship, however, has reworked habitability into a broader analytical framework that encompasses social, cultural, political, and economic dimensions (Sterly, Borderon, Sakdapolrak, et al., 2025). In this view, habitability is not a fixed or binary condition, but a relational and differentiated quality of places that varies across populations and over time. This reconceptualisation is particularly important for research on environmental mobilities, as it moves beyond linear explanations of migration under environmental stress to ask how, under what conditions, and for whom places remain habitable in the context of environmental and climatic change.

Contributing to this conceptual reorientation, recent theoretical advances have significantly deepened the analytical scope of habitability. Horton et *al.* proposed a multidimensional framework including "human safety, livelihood security, and adaptive capacity", while calling for integration of top-down assessments and bottom-up lived perspectives (Horton et al., 2021). Vinke further identified multiple dimensions of habitability: loss of territory, physiological limits, increased frequency of extreme events, and decreasing human security (Vinke, 2022). The same year, the Åbo Akademi University published its habitability index incorporating 45 indicators across seven domains (Abo Akademi University, 2022). O'Byrne's contribution to the Population-Environment Research Network (PERN) Cyberseminar (O'Byrne, 2023) suggested a normative definition grounded in Amartya Sen's capability approach, framing habitability as a set of substantive freedoms that enable individuals and communities to pursue healthy, meaningful, and dignified lives. The concept also incorporates tele-connectivity (Adger, Eakin, et al., 2009), (Adger, Eakin, et al., 2009), emphasizing the relational dimensions of places as shaped by connections across space and scale, including biophysical systems, economic linkages, and flows of resources, people, and information. These dimensions are often insufficiently addressed in more conventional vulnerability or resilience frameworks, yet they are central to understanding habitability in an unequal and interconnected world (Sterly, Borderon, Sakdapolrak, et al., 2025).

Clarifying the analytical contribution of the habitability concept requires situating it in relation to alternative ways of conceptualising environmental change, livelihoods, and human-environment relations in different disciplines and subdisciplines. A habitability framework may be particularly appropriate for researching environmental migration in contexts where change does not manifest as a sudden onset but rather through gradual, long-term processes. Vulnerability and resilience frameworks have often been operationalised in ways that prioritise discrete hazard events and short-term responses rather than the cumulative, long-term processes through which habitability deteriorates

(Blaikie et al., 2014; Kelman et al., 2015). Livelihood adaptations in contexts of slow-onset environmental degradation, such as recurrent droughts, often take the form of short-term survival strategies that enable immediate coping but may come at the expense of longer-term adaptive pathways. Over time, the accumulation of such responses can contribute to the precarisation of living conditions. Examining the temporality, where habitability slowly deteriorates under cumulative pressures and successive survival responses, requires specific analytical attention (Garcia et al., 2025; Sterly, Borderon, Sakdapolrak, et al., 2025). To grasp these gradual and differentiated processes, it is also necessary to adopt methodological approaches that explicitly account for time and the multiple dimensions through which environmental risks are experienced. Beyond material conditions, changes in habitability are closely intertwined with dimensions of well-being, socio-cultural relations, and psychological experiences that shape how risks are perceived, negotiated, and lived (Ayeb-Karlsson & Uy, 2022). A growing number of academic studies draw on ethnographic and mixed-methods approaches to better understand these lived realities and the populations concerned, aspects that are often more readily captured through narratives than through survey instruments (Tubi & Israeli, 2023; Borderon et al., 2021).

The renewed concept of habitability builds on these methodological and theoretical advances by offering a more inclusive and relational understanding of adaptation in contexts of environmental change. As noted by Sterly et al. (2025), population- and household-level resilience frameworks typically emphasise recovery from shocks. In contrast, habitability explicitly encompasses proactive adaptation and transformation processes. It extends beyond standard physical and material indicators to include spiritual connections to place, cultural meanings, and the political dimensions through which environmental change is experienced and governed. In this sense, habitability foregrounds intersectionality and social differentiation, recognising that changes in environmental and socio-economic conditions affect individuals and groups unevenly, depending on gender, age, socio-economic position, and other social categories. Habitability is thus inherently relational and livelihood-specific: dryland savannahs, for instance, may remain habitable for pastoralists while becoming increasingly unsuitable for farmers, underscoring how livelihood systems shape experiences of habitability (Sterly et al., 2025). This relational perspective is further illustrated by Mallick et al.'s (2025) concept of "tethered resilience," which emphasises place attachment grounded in rootedness, cultural ties, intergenerational learning, and individuals' embeddedness within socio-institutional networks. Together, these elements form the social and cultural landscape within which people negotiate opportunities, aspirations, and identities, and ultimately make highly context-specific decisions about adaptation, mobilities, or staying in place. From this perspective, sustained ethnographic attention to kinship relations and to individuals' embeddedness within families, lineages, and communities are important for understanding how habitability is maintained or eroded over time.

Mobility thus emerges as one among several strategies through which habitability is maintained, negotiated, or contested. Short-distance, temporary, and seasonal movements are often integral to livelihood strategies that sustain habitability over time (Garcia et al., 2025; Mallick et al., 2025; Sterly, Borderon, Sakdapolrak, et al., 2025). In the increasingly degraded Southwest interior coast of Bangladesh, for example, seasonal migration of daily workers enables families to remain within their community, albeit at the cost of physically demanding labour that exceeds the capacities of older adults (Clech et al., 2024). Similarly, in drought-prone rural area Kersa, Ethiopia, patterns of (im)mobilities reveal differentiated responses: elderly individuals often remain immobile and rely on informal support networks;

poor farmers engage in small, need-driven movements that allow them to stay in their villages; while young mothers from destitute households undertake mobilities as a survival strategy, frequently through begging (Garcia et al., 2025). In other words, declining habitability may manifest not only through migration but also through immobilities, micro-mobilities and translocality when capabilities to move or aspirations to leave are constrained (Garcia et al., 2025; Borderon & Garcia, 2025; Boas et al., 2025; Sterly, Borderon, Sakdapolrak, et al., 2025; Transiskus & Gholamzadeh Bazarbash, 2024; Sakdapolrak et al., 2024). Migration and immobilities are therefore multifaceted responses embedded within broader livelihood strategies.

Moving beyond the humanities and the social sciences alone, interdisciplinary collaborations across the social, biological, and physical sciences have sought, for decades, to conceptualise environmental change, livelihoods, and human-environment relations by defining concepts and frameworks, such as socio-ecological systems, biocultural interactions, biocultural diversity, ecological habitat, and niche. In the following, we present these different traditions, their convergence and interconnections, and how the "habitability concept" relates to them.

Social-ecological system (SES) frameworks were developed to examine interactions between social and ecological systems, as well as their evolution and adaptation (Biggs et al., 2021; Colding & Barthel, 2019; McGinnis & Ostrom, 2014; Ostrom, 2009; Partelow, 2018). Depending on research objectives, such frameworks are conceptually flexible, accommodating both ecocentric and anthropocentric perspectives on the ecological system, and can serve as either action-oriented or analysis-oriented (Binder et al., 2013).

A great variety of frameworks, definitions, disciplines and methodologies (Biggs et al., 2021) have been used, often in an operational sense, to understand functions, mechanisms and resilience of such systems, especially in environmental, development, sustainability and conservation sciences. When used for migration studies, social-ecological systems draw the context and its dynamics. For example, in Bangladesh, socio-ecological systems provide livelihood contexts and information on livelihood resilience, which inform migration decisions (Mallick, 2019; Mallick et al., 2020). Different livelihoods might rely on different ecosystems services (services provided by the ecosystem to sustain livelihoods, Millennium Ecosystem Assessment, 2005 (Millennium Ecosystem Assessment, 2005)) within the same social ecological system, and power dynamics around those services might limit the adaptive capacity of the poorest (Clech et al., 2024), with seasonal out-migration becoming an increasingly common response in a community of South-West Bangladesh.

For Folke (Folke, 2006), a holistic approach is needed to study social-ecological systems because they are complex adaptive systems (CAS, developed in Part 5) that integrate non-linear interactions, thresholds, uncertainty, multiscale interactions and feedback loops. By acknowledging the complexity of social-ecological systems and their resilience (both in terms of persistence and renewal capacity), Folke addresses deterministic, predictable and mechanistic critiques. Later, Biggs et al, (Biggs et al., 2021) confirmed the interest of studying social-ecological system as complex adaptive system by defining seven principles to avoid the reductionist pitfalls of maximisation and optimisation and allow greater resilience for ecosystem services: 1-maintain diversity and redundancy, 2-manage connectivity, 3-manage slow variables and feedbacks 4- foster an understanding of social-ecological systems as complex adaptive systems, 5-encourage learning and experimentation, broaden participation and promote polycentric governance systems.

Critics (see review in (Stojanovic et al., 2016)) have argued that such approaches are more ecocentric than anthropocentric (Daoust & Selby, 2024) and narrow the scope of social sciences by privileging quantitative studies coupling social and ecological components while marginalising interpretive and qualitative traditions within social research. In responses to these critics (Stojanovic et al., 2016) emphasised that the approach "remains relevant because of the central insights concerning the dynamic coupling between humans and the environment, and its salient critique about the need for multidisciplinary approaches to solve real-world problems, drawing on heuristic devices".

Unsurprisingly, for the past two decades, social-ecological system perspectives have evolved to integrate holistic dimensions, now encompassing cultural ecosystems services (Quintas-Soriano et al., 2018), intangible cultural heritage (Bodin & Tengö, 2012), sense of place (Masterson et al., 2019) and equity (Leach et al., 2018) among other considerations.

The habitability concept is not intended to stand apart from social-ecological frameworks particularly when the latter are understood as complex systems (Boas et al., 2025; Sterly, Borderon, Sakdapolrak, et al., 2025). Rather, it highlights material and immaterial dimensions of human life, that remain insufficiently addressed within social-ecological system frameworks (Sterly, Borderon, Sakdapolrak, et al., 2025). This suggest that the inter-, trans- and cross-disciplinary ambitions of social-ecological systems as a boundary concept are not yet fully realised. In this context, habitability does not seek to replace the social-ecological framework but rather to shed further light on the relational and value-based dimensions that are often only implicitly considered within it. By naming habitability as a distinct analytical focus, these issues, particularly those linked to inequality, power and differentiated vulnerability, become more visible and central to analysis.

For Merçon et al., 2019, the biocultural paradigm overlaps strongly with the social-ecological systems framework and acknowledges a plurality of human-environment interactions and worldviews. Biocultural approaches focus on the links between cultural and biological diversities, human well-being and social justice (Merçon et al., 2019). This allows researchers to represent and examine the diverse human and cultural dimensions of complex social-ecological systems (Hanspach et al., 2020 for review). Such approaches draw on multiple disciplines ranging from demography, biological and medical anthropology, evolutionary sciences, anthropology and ethnobiology, ecology, conservation, economics and even archaeology, resulting in multiple definitions and conceptual frameworks (Dufour, 2006; Hoke & Schell, 2020; Wiley & Cullim, 2016). Given this interdisciplinary heterogeneity rooted in converging traditions, we will consider here only a few key perspectives, each with its own discipline roots and ramifications.

Some of the earliest biocultural research used a biological anthropology lens, focusing on how culture and the environment shape bodies, physical development, health and adaptation (see Dufour, 2006; Hoke & Schell, 2020; Wiley & Cullim, 2016 for historical considerations). This approach was later enriched by attention to the political, economic and social contexts to understand biological processes and their evolution, at the nexus of ecologies, societies and histories (Leatherman & Goodman, 2020).

Later, ethnobiology, conservation and linguistic anthropology, concerned with how culture, knowledge, language, and practice co-evolve with biodiversity, developed their own biocultural approaches through the biocultural diversity lens. This interest, converging with indigenous peoples' concerns about the exploitation of their knowledge and the rapid deterioration of biocultural diversity, led to the Declaration of Belem (1988), issued by the International Society of Ethnobiology, which established that cultural and linguistic diversity

are inextricably linked to biodiversity. Environmental migration can have both positive and negative effects on people and biodiversity, constituting a complex phenomenon rather than a simple issue. While some form of migration may contribute to maintaining and protecting biodiversity, for example, in the context of traditional pastoralism (Briske et al., 2026), other types of mobilities might represent major threats to biocultural heritage. Because of migration, connections to land, traditional practices and intergenerational knowledge transmission may be jeopardised (Aktürk & Lerski, 2021).

Biocultural approaches converge on the idea of bridging the gap between nature and culture: they examine how social, cultural, economic, and environmental relationships are embedded in bodies, practices, and interactions with the environment. Today, these two perspectives (the biological anthropology tradition and the biocultural diversity tradition) are complementary, even though they are different (Franco, 2022). The first focuses on how culture and environment shape human biology, development, health, behaviours, and adaptations, while the second examines the co-evolution and inextricable linkages among biological, cultural, and linguistic diversity. These perspectives converge particularly within health, nutrition and wellbeing frameworks, and recent developments include the importance of integrating the local population participation and co-construction. These frameworks increasingly integrate considerations of biodiversity conservation, ecosystem health, inequality embodiment and local/global contexts (among other considerations) (Koster et al., 2024; Marselle et al., 2021; Sterling et al., 2017, 2020).

The reemergence of the habitability concept could gain greater analytical traction by examining developments in social-ecological systems frameworks and biocultural approaches. Rather than standing in opposition to or replacing these frameworks, habitability may be considered a complementary lens that clarifies the conditions under which the relationship between a population and a place remains viable over time. It maintains its own conceptual focus while allowing the inclusion of biological, ecological, and physical dimensions without relying on them.

To clarify both differences and similarities with related concepts, we conclude by discussing the convergence and differences with concepts commonly used in biological anthropology, evolutionary anthropology, and human behavioural ecology, which are not exclusive from the ones cited earlier. Despite the same etymological roots (from the Latin habitare, "to dwell, to live in"), the habitability concept has evolved independently from the "habitat" concept and its variations (Hall et al., 1997, 1997) prevalent in ecological studies, though recent holistic developments of habitability may seem to converge with the ecological "niche" concept (and its variations) (Colwell & Rangel, 2009; Pocheville, 2015; Sales et al., 2021) or multidimensional resource allocation (social, material, biological etc.) perspective in human behavioural ecology (Jones et al., 2021; Koster et al., 2024; Nettle et al., 2013; Sear et al., 2024). For example, kinship, land inheritance, and drought influence who leaves the household in rural Ethiopia (Clech et al., 2019, 2020). The ecological "niche" describes an organism's role within its ecosystem, including physical habitat and functional interactions (to other individuals, other species, ecosystem, etc.) (Pocheville, 2015; Sales et al., 2021). Through niche construction, organisms actively modify or engineer their environments, thus influencing evolutionary pressures. While the human ecological niche has been discussed at the species level (Hamilton, 2025) and acknowledged in habitability papers through the idea of "narrowing" or "shrinking" climate niche (Xu et al., 2020 in Boas et al., 2025 and in Sterly et al.2025), anthropology and evolutionary human sciences apply the human niche or idea of multidimensional environment and resources also at lower level

(community, household and individual) and in a more broad sense where culture serves as both an environmental element and driver of human-environment interactions (Ready & Price, 2021).

However, the question of ecological niche centres first on the conditions for survival and reproduction of individuals, family groups, communities or (sub) populations in relation to their environment, while the concept of habitability focuses mostly on the sustainability characterisation of a territory for an individual, household, community or population, suggesting a different angle of the same subject (population-environment) from both concepts.

Finally, Boas et al. (Boas et al., 2025) recommend five considerations for research on habitability, placing principles of equity, dignity and justice at the core of their framework: 1. Do not impose hard limits to habitability unless an interdisciplinary approach and local knowledges and populations are included 2. Treat projections as possible futures, not the inevitable future 3. Don't assume the Global North is harm-free and homogenous 4. Enable people's right to stay 5. Invest in in-situ adaptation and social equity. The authors advocate for bottom-up approaches and people-centred perspectives to avoid adverse effects on local populations. In terms of methodology, habitability research could seek to employ methodological pluralism, with interdisciplinary and transdisciplinary approaches, mixed method designs integrating quantitative modelling (including complex modelling and econometrics) and qualitative insights from local communities (ethnographic studies, participatory approaches, narrative analysis, and discourse analysis) (Boas et al., 2025; Sterly, Borderon, Sakdapolrak, et al., 2025; Blocher et al., 2025).

Case study 5: A preliminary research on habitability in Kersa, Ethiopia

Methodology: The study was conducted in Kersa district in Eastern Hararghe, Ethiopia, a predominantly rural and drought-prone area where livelihoods rely heavily on rain-fed subsistence agriculture and where multiple environmental and socio-economic pressures intersect (Garcia et al., 2025). The research adopted a sequential explanatory mixed-methods design in which qualitative inquiry was used to deepen and contextualise quantitative findings on household habitability and mobilities. The objective was to examine how environmental stress interacts with social differentiation, local livelihood systems, and broader forms of connectedness to shape changing conditions of habitability and mobilities patterns. The quantitative component drew on data from the Kersa Health and Demographic Surveillance System (HDSS), which covers 12,494 households, and informed the development of a multidimensional household-level assessment of habitability. This was complemented by qualitative fieldwork conducted in September 2022, including semi-structured interviews, focus group discussions, ethnographic observations, and participatory mapping exercises. Together, these methods made it possible to analyse not only material living conditions and perceived well-being, but also local understandings of environmental change, livelihood insecurity, and mobilities, as well as the social and spatial relations connecting Kersa to other places.

Findings: Major findings revealed that declining habitability in Kersa is not the result of environmental stress alone, but of the cumulative interaction between ecological degradation, demographic pressure, livelihood precarity, and weak institutional support. Recurrent drought plays a central role, but it unfolds within a broader context marked by soil degradation, land fragmentation, limited non-farm employment, fragile educational infrastructure, and increasing dependence on unstable income sources. The expansion of

khat cultivation illustrates these tensions particularly well: although it offers immediate year-long financial returns, it also contributes to the abandonment of food crops, pressure on water resources, and growing dependence on volatile market dynamics (Sterly, Borderon, Sakdapolrak, et al., 2025). The findings further highlight that habitability is experienced in highly differentiated ways across the population. Social position, gender, age, and access to land or financial resources strongly shape both exposure to declining living conditions and the capacity to respond. Poorer or landless households are more vulnerable to shocks and often less able to use mobilities as a strategy, whereas better-off families may be able to finance labour migration for younger household members. In this context, migration emerges primarily as a short-term, reactive survival strategy rather than a pathway to upward mobility. Movements are often short-distance, circular, and informal, undertaken to compensate for food shortages, cover school or health expenses, or repay debts. At the same time, the capacity to move is itself unequally distributed. Some individuals remain in precarious conditions due to age, gendered responsibilities, or a lack of resources, while others are pushed into precarious labour circuits. The study therefore shows that both habitability and mobilities are deeply socially differentiated (Borderon & Garcia, 2025; Garcia et al., 2025). A further key finding concerns the role of connectivity. Mobility networks and social relations that extend beyond the immediate locality shape households' capacity to cope with deteriorating conditions. These connections may support local habitability by providing access to income, information, and social support, while also revealing that the viability of place is linked to processes operating across scales rather than being solely determined locally.

Debates, limitations and lessons learned: Several limitations should be acknowledged. First, although the HDSS provides a robust quantitative basis, it cannot fully capture subjective, relational, and place-based dimensions of habitability, such as attachment to place, perceived dignity, or culturally grounded understandings of well-being. Second, the empirical material reflects a limited temporal window and therefore cannot fully account for seasonal variation or longer-term changes in environmental conditions, livelihood trajectories, and mobilities practices. Third, while the study highlights social differentiation and institutional fragility, it offers more limited insight into the power relations that shape local habitability, including the role of state policies, uneven access to adaptation support, and local authorities' actions in mediating resources and assistance. These limitations point to the need for more longitudinal and politically attuned research on the changing production of habitability.

Synthesis on habitability

The habitability concept presents both significant advantages and limitations for environmental mobilities research. Conceptually, the framework's holistic integration of environmental, socio-cultural, economic, and political dimensions offers a comprehensive understanding of place-based challenges that traditional single-sector approaches cannot achieve. Its future-oriented perspective enables anticipatory action by identifying early signs of a decline in habitability, potentially preventing displacement crises. The emphasis on intersectionality and local perspectives promotes climate justice and inclusive decision-making processes, addressing power imbalances often overlooked in environmental mobilities research. By contrast, top-down framings can contribute to a decline in habitability by discouraging local investment, withdrawing public services, and legitimising institutional

disengagement, thereby undermining local livelihoods and, through governance choices, producing uninhabitability (Boas et al., 2025; Sterly, Borderon, Sakdapolrak, et al., 2025).
Methodologically, habitability research demonstrates considerable flexibility in accommodating diverse data sources and analytical approaches. However, challenges remain in integrating top-down systemic and bottom-up local perspectives due to methodological and epistemological differences (Horton et al., 2021). Reconciling materialist and spiritual worldviews is particularly complex, and establishing objective thresholds and tipping points for habitability remains difficult, especially when accounting for subjective and culturally embedded perceptions (Janoth et al., 2024).
Emerging ideas from habitability research call for expanding the concept's scope to include planetary boundaries such as biodiversity loss, soil degradation, and freshwater use beyond standard climate indicators (Blanc et al., 2025). Increased interdisciplinary collaboration between different modelling approaches could better address nonlinearities and complexity in human-environment systems. Ethical considerations require continued attention to ensure local voices are included in habitability definitions and that research findings serve community interests rather than external political or economic agendas (Boas et al., 2025).
The global relevance of habitability extends beyond vulnerable populations in the Global South to include for instance demographic decline and shrinking cities in the Global North, offering valuable comparative insights. Ultimately, habitability provides a nuanced, holistic, and future-oriented framework for understanding environmental-social interactions that can inform equitable, context-sensitive policies to address climate change and other environmental challenges in migration contexts.

Collective reflection from the World Café

Most participants were unfamiliar with the concept of habitability, prompting a discussion of its differences from related concepts. Habitability centres on how environmental changes affect human life, emphasising territory quality and the interdependence between populations and their environments, which is not far from ethnobiological and socio-ecological perspectives on biocultural interdependencies. However, the concept of habitability, as developed in environmental migration studies, emphasises the "territorial dimension", namely, how political, infrastructural, and social processes shape collective and spatial conditions. In this sense, habitability extends beyond adaptation to interrogate how places themselves become (un)habitable within broader systems of power and inequality. This idea is strongly aligned with the call from Boas and Sterly to interrogate "the politics of habitability than the habitability of a place itself" (Boas et al., 2025; Sterly, Borderon, Sakdapolrak, et al., 2025). This recognises that powerful actors, such as states and private corporations, can actively shape which places are rendered habitable or uninhabitable through infrastructure development, resource extraction, or border control.

The concept has evolved significantly from its origins as a response to simplistic shrinking-human-niche narratives and population-redistribution models based on environmental tipping points. While early formulations focused on the physical qualities of the habitat, the most recent formulations (Sterly, Borderon, Sakdapolrak, et al., 2025) embrace complexity and nuances, incorporating subjective experiences of living conditions, inhabitant preferences and aspirations, highlighting the need for bottom-up approaches due to considerations of social and climate justice, and rights to move or to stay. Participants identified habitability as an umbrella concept encompassing multidimensional well-being,

vulnerability considerations and livelihood approaches. While similarities with livelihood frameworks were acknowledged, more work is needed to understand what habitability uniquely offers. For example, the (material and fictive) territorialisation of livelihoods, the inclusion of power dynamics, and the ethical consideration of the rights to stay or move have been cited and have been echoed in the literature (Boas et al., 2025; Sterly, Borderon, & Sakdapolrak, 2025; Sterly, Borderon, Sakdapolrak, et al., 2025). The distinction between habitability and liveability remained unclear and warrants further clarification. This is unsurprising, as the concept has only recently reemerged and been (re)developed, and it still needs further development to reach full conceptual maturity.

The relationship to ecological concepts of habitat and niche received limited attention, yet this parallel mirrors the terminological challenges that ecology has navigated through conceptual renaming. Questions arose about whether to preserve the existing terminology, noting that the etymological foundation remains closer to the initial conceptualisation despite substantial evolution. Key methodological challenges emerged from the discussion: reconciling bottom-up population involvement with top-down policy approaches, developing measures for self-evaluating habitability that enable territorial and social-group comparisons, and addressing the temporal and spatial variability of social-group preferences and aspirations. The sustainable livelihoods framework was retained as a methodological foundation to reconstruct the sequential logics of adaptation within the studied communities. For example, Jarillo and Barnett (Jarillo & Barnett, 2024) suggest adopting a longitudinal perspective on the five asset pillars of the livelihood pentagon (Scoones, 1998), examining how changes in these resources over time intersect with and shape observed migration trajectories. Finally, multidimensional well-being indices were proposed as potential starting points for capturing habitability values, though measurement standardisation remains an ongoing challenge as demonstrated in biocultural approaches (Betley et al., 2023; Sterling et al., 2017, 2020).

Part 5 - Methodological challenges in environmental migration and (im)mobilities studies

As presented in previous sections, the concepts of compound hazards, livelihoods, and habitability are central to understanding environmental migration and (im)mobilities. These concepts represent different disciplines, traditions, methodologies, and perspectives on environment-population interactions, and they intersect, overlap, encompass, or complement other approaches, such as social-ecological systems, biocultural diversity, ecological concepts of habitats and niches, and the concepts of crisis and polycrisis.

Collectively, these frameworks reveal the growing complexity of research on population migration and (im)mobilities. Scholars increasingly recognise that environmental migration and (im)mobilities result from multiple interacting factors operating across scales, from individual decision-making to global environmental change, with non-linear dynamics, thresholds, uncertainty, feedback loops, and emerging patterns (such as new types or new frequencies of migration, or (im)mobilities). This complexity brings methodological challenges for researchers seeking to analyse and model environment-migration relationships.

The complex adaptive systems (CAS) approach (section 5.1) offers a powerful way to integrate these multiple conceptual perspectives and capture the dynamic, multi-scale interactions that characterise migration and (im)mobilities (United Nations Environment Programme, 2023). Agent-based modelling enables the simulation and exploration of individual behaviours and their emergent collective outcomes within complex adaptive systems. However, implementing such approaches, or even other frameworks as presented in earlier sections, raises additional challenges related to analytical tools, data availability, data correspondence and empirical validation methods (section 5.2).

Conceptual Integration and Modelling: Complex Adaptive System Approach and Agent-Based Modelling

Conceptual foundation

Environmental migration and (im)mobilities present inherent complexity: compound hazards with complex continental and oceanic factors interacting in case study 2 (Khan et al., 2025), complex human responses where some populations migrate while others remain in place in case studies 1, 3, 4 and 5 (Garcia et al., 2025; Mallick et al., 2020; Mallick & Hunter, 2024; Warner & Afifi, 2014), the critical importance of policies that can either facilitate or constrain mobilities options (not presented in the case studies), the different livelihoods and socio-ecosystems suggesting different context and pathways in hazard-migration (Clech et al., 2024; Mallick et al., 2020; Warner & Afifi, 2014), the multidimensional development of the concept of habitability (Boas et al., 2025; Sterly, Borderon, & Sakdapolrak, 2025; Sterly, Borderon, Sakdapolrak, et al., 2025) and the necessity for bottom-up approaches that recognize local agency and knowledge systems. Thus, as a social-ecological system (Folke, 2006; Gunderson & Holling, 2002), the climate-environment-migration nexus function as a complex adaptive system (CAS) rather than multiple linear causalities (Carmichael et al., 2019; Carmichael & Hadžikadić, 2019; United Nations Environment Programme, 2023) that could be represented, at different scales, as a networks of interacting entities ranging from climate patterns and ecological processes to households, communities, institutions, and

governance structures that create emergent migration/(im)mobilities patterns without centralized control.

Without control, because complex adaptive systems (CAS) exhibit two fundamental properties: complexity (requiring multiple disciplinary perspectives to understand the interplay between environmental degradation, social vulnerability, and mobility decisions) and intractability (migration pathways evolve through time with countless possible trajectories that cannot be predicted). This means no single actor can fully comprehend or control migration flows. Non-linear coevolving relationships can be considered, and feedback loops are of particular interest. Responses to hazards (e.g., migration, changes in livelihood activities) by individuals, households, or communities influence community dynamics, which in turn affect local institutions, which shape policies, which, in turn, influence future responses to hazards (and thus migration, changes in livelihood activities, etc.). In other words, complicated systems, despite having many elements, operate in predictable ways, whereas complex systems, as here, generate unpredictable emergent phenomena, such as environmental mobilities. The complexity and adaptivity of complex systems cannot be ignored without unintended disastrous consequences for the entities within the systems (social groups, populations, ecosystems etc.).

This approach enables understanding of the system's dynamics, with a focus on feedback within and between the systems that compose it. For example, in Tala Upazila, south-west Bangladesh (Clech et al., 2024), farmers are increasingly adopting shrimp farming in response to environmental change and to economic, market, and governance incentives (case study 6). This shift transforms their social-ecological system through feedback loops among the socio-economic and ecological systems and among livelihood pathways. However, whether this behavioural response can be considered as a transformative adaptation (Fedele et al., 2019) remains unclear. While this shift in livelihood pathways alters the ecological and social properties of the system, it does not address the root causes of vulnerabilities to climate change nor lead to a more just, sustainable, and resilient system (Fedele et al., 2019). Moreover, this transformation creates an even greater power imbalance in the community and further constrains the adaptive capacities of other livelihoods. Because of reconfigurations in land and water use, access to natural resources, and the local job market, landless, low-skilled workers increasingly rely on seasonal out-migration, particularly to brick factories. Whether this translocal livelihood represents a new form of mobility, at least in terms of frequency and occupations, or rather a transformation of older rural labour mobilities (in agriculture and fishing) within a fluctuating deltaic system, remains an open question.

Understanding environmental migration and (im)mobilities as a production of complex adaptive systems necessitates incorporating power dynamics and structural agents (i.e. examining how inequality, land tenure systems, and socio-political marginalisation shape migration options, how the response to the hazard of some impacts the options of others), maintaining a people-centred perspective that recognises migrants' agency and diverse adaptation strategies in their environment. This requires employing transdisciplinary approaches that integrate climate science, social research, policy analysis, and community knowledge. This approach is not exclusive of vulnerabilities, livelihood or habitability frameworks; on the contrary, it can be inclusive of those concepts and frameworks. For example, Biswas & Mallick, 2021 apply a quantitative livelihood approach to understand seasonal migration as a livelihood diversification strategy under climate-induced environmental change in coastal Bangladesh. Converging findings from Clech et al. (2024)

further integrating multiple livelihood pathways through ethnographic data and quantitative climate analysis on four types of livelihoods, while (United Nations Environment Programme, 2023) illustrate the flexibility of this approach to different frameworks (i.e. vulnerability, sustainable livelihoods, new economics of labour).

From a pragmatic perspective, the CAS modelling approach has several advantages. In contexts lacking quantitative data, this approach may help to understand local contexts from the population's perspective, including their experiences, motivations, and aspirations for migration (qualitative and participatory data). Coupled with physical and biological data, this resulting hybrid approach allows comparison of perceived versus measured physical and biological variables, revealing potential mismatches between subjective experiences and objective conditions. Moreover, it can serve as an exploratory phase, using an inductive approach to capture the complexity of local contexts, mobilities trajectories, and potential causal mechanisms, thereby informing the development of research questions and hypotheses on migration and other livelihood strategies. A complex adaptive system modelling approach can also integrate diverse forms of resources: tangible assets such as household assets and infrastructure, and intangible elements such as community networks, cultural heritage (including biocultural heritage), and spiritual beliefs. Finally, transdisciplinary mapping of complex adaptive systems with local communities or social groups enables the integration of different perspectives, builds collective understanding, and serves as a powerful visual tool for communication and decision-making with stakeholders and policymakers (Ghorbani et al., 2024).

To explore specific hypotheses, such as the strength of causality in the phenomenon's emergence, minimalist scenarios can be tested using various methods, including agent-based modelling, machine learning, game-theoretic models, system dynamics, discrete-event simulation, cellular automata, network models, and Markov models. Due to the unpredictability of complex systems, those scenarios are used prospectively rather than predictively.

Here, we will discuss agent-based modelling (ABM), a computational approach well-suited to exploring multiple scenarios by representing and analysing complex adaptive systems. ABM are composed of autonomous entities (*agents*) interacting within an environment. *Agents* are autonomous programs that perceive, decide, plan, interact, communicate, and adapt in *environment*s that can be physical, social, or abstract, or even act as agents. Agents may interact with one another and with the environment, creating feedback loops. In the context of environmental migration and (im)mobilities, ABM helps capture a diversity of migration responses and the interactions between environmental and socio-economic factors. They show that migration patterns emerge from these interactions rather than from single causes and that climate and environment interact with existing mobilities systems, including return migration and immobilities dynamics (Salerno et al., 2024; Entwisle et al., 2020; Smith, 2014; Hassani-Mahmooei & Parris, 2012). And finally, ABM may be used to understand dynamics, experiment *in-silico*, prospect future states, explore scenarios, and assess policies.

We classically distinguish three approaches (Chapuis et al., 2022) to agent based modelling: the seminal KISS (Keep It Simple, Stupid!) models (Epstein & Axtell, 1996) rely on abstract (i.e. in opposition with empirical) and simple mechanisms (i.e. easy to understand and to process mentally), focusing on macro-level emergent properties, explicability and Occam's razor principle (found the least complex set of entities, relations and properties of the model able to generate targeted system outcomes). The objective of such models is to

better understand processes and mechanisms of target systems, often taken in isolation. The KIDS (Keep It Descriptive, Stupid!) approach later popularised by (Edmonds & Moss, 2005) makes great use of data either in conceptual design and specification of simulation inputs, while focusing on empirical demonstration or the description of collective emergence phenomena. The common goals of such models are to support decision-making by providing detailed explanations and prospective properties of simulated systems and subsystems. The latest group of ABM models, labelled KILT (Keep It a Learning Tool) (Le Page & Perrotton, 2017), displaces the properties that the agent-based modelling process focuses on from the model content to the process of co-designing the model, hence focusing on collective outcomes of the modelling process itself by leveraging the intuitive concept used in building agent-based models. The targeted outcome is less about gaining knowledge or supporting a decision than empowering actors and building collective momentum through social learning.

Complex systems cannot be predicted from their individual components alone. Still, ABM, by focusing on specific mechanisms within the system, can help explain the key mechanisms driving the emergence of collective patterns. Considering future scenario projections, adaptive management approaches that embrace uncertainty and foster collaborative learning are preferable to predictive models, ensuring both environmental justice and democratic participation in scientific processes.

ABM applications are not limited to voluntary migration. They are also relevant to the issue of forced displacement, where the distinction between voluntary and forced movement can be seen as an emergent property of the system rather than a fixed condition. Within the computational sciences, machine-learning-based models and agent-based modelling (ABM) have become powerful tools for understanding dynamics of (forced) displacement in humanitarian contexts (Ghorbani et al., 2024). Researchers have applied these modelling approaches to explore displacement driven by conflicts and environmental factors and to estimate the potential impacts of various conflict or intervention scenarios (Ghorbani et al., 2024; Jahani et al., 2021; Vanhille Campos et al., 2019; Suleimenova et al., 2017; Groen, 2016). While previous sections did not cover forced migration, it is important to note that the distinction between voluntary and forced displacement is blurred and operates along a continuum of constrained agency rather than a binary condition (Erdal & Oeppen, 2018; IOM, 2019). For instance, resource scarcity, such as drought, can indirectly fuel conflict and displacement. Similarly, farmers facing the gradual loss of arable land due to erosion or rising sea levels may be forced to relocate. Thus, forced versus voluntary framings carry significant political stakes in how populations are categorised, protected or excluded from national and international legal frameworks.

Recent advances in simulation demonstrate the growing sophistication of these modelling methods. For instance, Flee 3 (Ghorbani et al., 2024) is an agent-based simulation tool designed to explore migration patterns using adaptable rules for agent movement (displaced agents or migrants), while incorporating factors such as food security, ethnicity, religion, gender, and/or age. The model was validated by applying it to 10 historical conflicts in Asia and Africa and, when compared to UNHCR refugee data, correctly forecast up to 70% of refugee arrivals. This approach (Ghorbani et al., 2024) was coupled with verification, validation and uncertainty quantification (Roy & Oberkampf, 2011).

According to Ghorbani et al., 2024, ABM are well suited to data-poor contexts, where qualitative or participatory data may be collected as empirical evidence to define behaviours and system mapping that will be coded in the models. In addition, ABM allows for different

levels of complexity by integrating complex behaviours arising from the interaction and aggregation of agents, as well as from agent-environment interactions.

System mapping and modelling may involve mixed interdisciplinary and transdisciplinary methodologies combining qualitative social science and behavioural approaches (ethnographic fieldwork, interviews, focus group discussions, questionnaires, observations), participatory mapping (through focus groups and workshops), quantitative analysis of physical, ecological, and social sciences data, transdisciplinary and interdisciplinary collaborative work for modelling and computational modelling for test of scenarios.

Case study 6: Mapping livelihoods and seasonal migration in southwest Bangladesh: a complex system approach

Methodology: The study (Clech et al., 2024) is part of a mixed-method sequential exploratory project on climate change, migration, and health system resilience in Bangladesh and Haiti, the ClimHB project (Clech et al., 2022; Ridde et al., 2025). It focuses on the resource-mobility nexus, treating natural resources as ecosystem services that support livelihoods, across four types of livelihoods in a rural community in southwestern Bangladesh: agricultural farmers, shrimp farmers (or agro-shrimp farmers), independent fishermen, and daily labourers (landless). The methodology is structured around three main parts: (1) short ethnographic exploratory fieldwork with qualitative data collection (50 respondents interviewed during semi-directed interviews and focus group discussions), (2) analysis of rainfall patterns and trends (1981-2021) using secondary data (CHIRPS data verified with nearby forecast station records) to compare with community perception, and (3) mapping of system functioning through a complex adaptive systems perspective, integrating feedback loops, as seen by the community.

Results: The community's knowledge and perception of environmental degradation over the past 25 years align with changes in rainfall patterns. In this community of farmers, the context of compound hazards and polycrisis results in complex responses. Shrimp farming is increasingly adopted, but it limits the options for the landless (fewer access to free water, fewer local job opportunities and a feedback loop: more shrimp farming means more waterlogging, which means fewer agricultural lands and fewer agricultural jobs). Rural-rural seasonal low-skilled migration is a response for some to remain in their community part of the year, but it is a risky strategy; it may pay well, but it is physically demanding and entails additional risks for them and the left-behind.

Debates, limitations and lessons learned: This study began as simple qualitative exploratory fieldwork but evolved during and after the fieldwork into a complex analysis that combined interviews, focus group discussions, observations, rainfall analysis, and mapping. The complex system approach was entirely new to all authors (social and public health scientists). This study was exploratory and focused on rural-to-rural migration in a specific area, the internal coast, a location subject to river tides. This may not be generalizable to all socio-ecological systems. Still, it is of interest because the studied community is next in line for environmental degradation, compared to the already devastated south. We did not fully account for important external factors (e.g., government policies, international markets) or family and community dynamics (e.g., land inheritance conflicts, household relationships, age- and gender-related vulnerabilities, etc.). Combining qualitative social science data with quantitative climate data was challenging due to the lack of guidance (i.e. handbooks or protocols) for this type of mixed research between social and physical sciences. Future

studies should involve the co-construction of transdisciplinary knowledge with local communities through collaborative mapping. Finally, complex adaptive system mapping might be especially relevant for understanding the complexity of local context(s), multiple non-linear causalities, and feedback loops before formulating and testing hypotheses for quantitative data collection.

For this study, selecting the timeframe and spatial scale for comparing ethnographic and physical environmental data was the first consideration. Satellite rainfall data were compared with rainfall data from forecast stations in the area for validation, enabling us to analyse rainfall at the local (community) and regional levels. The time frame selection for rainfall analysis was based on qualitative data on historical and intergenerational experiences of environmental change. Finally, among all hazards, rainfall data were pragmatically selected, as they reflect excess (heavy rains), shortage of rain (drought), and seasonal changes. However, for a full picture, as reflected in the system mapping, other hazards could also be considered, and this approach could encompass several study sites. This approach can also be used to project future hazards related to climate change. For this purpose, CMIP6–IPCC climate models that have been previously validated for the region can be analysed.

Case study 7: Agent-based modelling for Tsunami Evacuation

While previous case studies focused on migration, the following case study focuses on mobility during a catastrophic event. The Tsunami evacuation project (Carles et al., 2025) uses ABM to explore scenarios of pedestrian evacuation during tsunamis. The goal of the model is to simulate the effects of tsunami warnings on evacuation behaviour and to assess the effectiveness of alert systems in minimising risk and ensuring safety. It is relevant in the context of migration because the core feature of the modelled behaviour is 'milling time', a concept focusing on the time spent between alert awareness and the decision to leave. A key decisional and behavioural aspect of forced movement during a crisis. In our simulated virtual world, deciding not to move is equivalent to a longer preparation time than the one we simulate; in other words, we do not model the decision to move or not, but instead assume unlimited preparation time. However, we consider that a familiar environment plays a significant role in preparation time, which is longer for those in an unfamiliar environment

Methodology: The methodology driving the modelling process aligned with the KIDS approach, relying heavily on GIS, survey, and direct observational data, particularly for spatializing risk issues such as the population under threat, the occupation of public and private places, and the spatial distribution of the alert system. This last part has been built in cooperation with experts from national authorities (FranceAlert for the cell broadcast) and local stakeholders (the Siren system of the city of Cannes). In the following, we detail how the model has been built, and how the simulation has been initialised and used.

To locate agents in the Tsunami-prone area, the project uses GIS data to represent road networks, shelters, beaches, and other spatial elements of interest, like buildings and public spaces. The initialisation of the simulation also includes data on siren sound propagation (i.e., a raster layer that translates noise levels in dB from the noise modelling simulation), demographic data such as age, and, finally, survey data on milling time and knowledge of alert signal recognition. Agents are either inhabitants or tourists. Each has attached a hypothesis: the former has good knowledge of shelter locations but less incentive to respond quickly to evacuation guidelines, while the latter do not know where shelters are but feel pressured to respond as soon as they receive an alert signal. Agent behaviour is rather simple:

once an agent receives the alert, it prepares (i.e., milling time) and moves away from its location near the beach, either towards a known shelter or, otherwise, by trying to locate it from other surrounding agents. For scenario exploration, two alert systems (sirens and cell broadcasts) are modelled with delays - representing a dysfunctional upward alert, i.e. from hazard recognition to political decision - partial coverage - from low to high broadcast coverage/cellphone message efficiency - and malfunction - lower spatial coverage of siren, from no signal to full noise level diffusion.

Results from modelling highlights the importance of duplicated alert systems in raising awareness and enforcing evacuation, either to build resilience toward compounding hazard effects over alert vectors (e.g. due to defection during the chain of rising notifications from detection of Tsunami prompt seismic events to authorities in charge of launching alert vectors) or to build upon vectors synergies (e.g. cell broadcast can reach people outside of the siren noise coverage). Effective coverage and timely alerts significantly improve evacuation outcomes, especially in the case of exogenous disruptions such as bad weather (i.e. poor siren coverage) or vector disturbances (i.e. cell broadcast delays).

Debates, limitations and lessons learned: The model relies on overly simplified behavioural hypotheses, relies only marginally on agent knowledge, and does not account for agent interactions in micro-mobility during evacuation. In particular, milling time should consider social links between agents (e.g. being alone or with friends and/or family does not results in the same preparation time), knowledge of shelters location should not be either complete or none, evacuation guidelines should be taken into account in agent evacuation pathways and crowd movement as well as emotional contagion should drive at least partially movement of agent. From experience, ABM is interesting for an intuitive modelling perspective on social phenomena, for growing from the bottom up, for testing social mechanisms, for engaging with interacting individual entities, and for participatory modelling. ABM are not recommended when quick answers are required, when heterogeneity does not matter, when only global trends are of interest, or when time and HR are limited for coding.

Issues and Challenges in Data and Tools

In terms of methodology, as seen in the introduction and previous sections, the concepts, frameworks, and approaches are crucial to designing questions, hypotheses, and protocols. Data access is also critical for supporting hypotheses in empirical approaches. Environmental migration studies have evolved significantly, progressing from simple causal analyses to more elaborate frameworks that incorporate multidimensional perspectives, multiple pathways, and complex interactions. For quantitative and mixed-methods projects, the availability of quantitative data and the challenges of accessing and using it strongly influence the scope and advancement of research.

The tools fall into two categories: *ex ante* simulation models that explore hypothetical scenarios and *ex-poste* regression models that analyse observational data to estimate the association between climate-environmental events and migration/ non-migration outcomes. Within the second category, methodologies range from reduced-form regressions that measure the direct relation of climate-environmental events on various migration types (international or internal, temporary or permanent, flows or stocks, in-migration, out-migration or net migration) to more elaborate analyses focusing on complex chains of causality (i.e. drought > crop failure > lower income >diversification > migration). Different scales have different limitations: macro-studies hide within-country heterogeneity, while micro-studies offer several advantages and disadvantages. Large-scale household surveys,

although representative, provide only rough estimates of migration and generally lack a time dimension. Exhaustive, they refer to a single reference period and therefore provide only a limited number of migration measures, mainly through indicators of lifetime and recent migration. However, their combination with improved climate indices, such as the Standardised Precipitation Evapotranspiration Index (SPEI), and sophisticated GIS-based satellite data is contributing to methodological advances (Case Studies 8 and 9). Longitudinal surveys, by contrast, are usually small-scale, restraining the diversity of climatic and environmental events. In light of these methodological constraints, big data sources (such as phone Call Detail Records (CDR)) appear promising in terms of spatial and temporal granularity (Case study 10). But they also introduce new challenges, such as temporal and spatial matching with climate data, as well as concerns about privacy, data-processing complexity, and population representativeness.

Three case studies illustrate the use of quantitative data across different contexts and methodological approaches (cases 8, 9, and 10).

Another methodological approach that deserves attention, though it is briefly touched upon in the hazard section (Part 2), is the potential of remote-sensing-derived datasets, particularly in data-poor regions. Beyond their well-established role in physical and hydrological modelling, remote sensing datasets allow the identification of vegetation dynamics, changes in built environments, and proxies for human activities, making them an interesting tool for scaling up environmental migration analyses. Their applicability in data-scarce contexts makes them a valuable complement to the approaches discussed here and merits further attention.

Finally, the FAIR principles (Findable, Accessible, Interoperable and Reusable) were designed to address the barriers to data access. Yet their adoption remains uneven, and the difficulty of locating suitable datasets documented throughout this article suggests that FAIR principles are either insufficiently implemented or insufficiently adhered to in practice. Greater alignment with FAIR data standards, particularly for environment -including climate- and mobilities datasets in the Global South, would help the field build more effectively on existing work.

Case study 8: Migration response to drought in Mali

This study (Defrance et al., 2023) investigates the relationship between drought exposure and migration dynamics in Mali over the 1987-2009 period.

Methodology: The study combines highly disaggregated population census data with georeferenced climate indicators, enabling analysis of approximately 11,000 localities nationwide. Migration is inferred from population changes between three national population and household censuses conducted in 19877, 1998 and 2009. In-migration, out-migration, and net migration (defined as the difference between in-migration and out-migration) rates are computed for each locality by age cohort and gender, based on intercensal population growth, after accounting for births and deaths. This approach allows capturing internal mobilities, which is often missing from survey-based migration datasets, but also raises important methodological challenges (measurement errors, underestimation of intercensal moves, etc.). Drought is measured using the Standardised Precipitation-Evapotranspiration Index (SPEI), a composite indicator that accounts for both precipitation and evapotranspiration. SPEI values are calculated on a 5x5 km grid and aggregated at the locality level. A year is classified as a drought year when the SPEI values fall by more than one standard deviation below the long-term historical mean (calculated from 1904 onward).

Using this threshold, for each intercensal period, the number of dry years and the number of dry agricultural seasons were computed. Analyses are based on panel regressions with locality and period fixed effects, included to control for time-invariant local characteristics and common temporal shocks. To address spatial and serial correlation in climate shocks, standard errors are corrected using the Conley (1999)-Hsiang (2010) approach. The models explicitly test for heterogeneous drought effects through interaction terms, reflecting differences in livelihood structures and adaptive capacity. To further account for unobserved common factors correlated with both climate and migration, interactive fixed-effects models were also estimated as robustness checks.

Results: Drought exposure is associated with increased out-migration rather than reduced in-migration, resulting in a decline in net migration rates in rural localities. This negative association holds for both men and women and across most age cohorts, but is attenuated or absent in urban localities, indicating that urban households' migration decisions are not affected by climate conditions. In addition, drought impacts are more noticeable in arid sites, poorer localities, and areas with low crop diversification, suggesting that adaptive capacities, as reflected in agro-ecological conditions, wealth, and crop diversity, mitigate migration responses. The number of droughts has also been found to increase international migration rates, primarily to neighbouring countries, suggesting that climate stress reshapes existing mobility patterns rather than triggering large-scale, long-distance movements.

Debates, limitations and lessons learned: This case study illustrates both the analytical potential and the limitations of combining high-resolution climate indices with census-based migration proxies. While panel fixed-effects models allow for fine-grained spatial analysis and control for unobserved heterogeneity, the results remain sensitive to model specification, fixed-effects structure, and the definition of climatic shocks. Reliance on the net migration rate does not allow more precise migration categories (temporary, circular, etc.), limiting insights into cascading, adaptive migration pathways or livelihood strategies. This case study underscores that identifying climate effects on migration requires balancing control of confounding factors with retaining sufficient climatic variation, and that quantitative results should be read as context-specific indications rather than exact causal effects.

Case study 9: International migration response to climate anomalies in Senegal

Previous work showed that a negative climate shock increases international migration flows (case study 8: Defrance et al., 2023). However, middle-income countries show a positive relationship between temperature and migration, whereas low-income countries present poverty-trap patterns (Beine & Parsons, 2017; Cattaneo & Peri, 2016).

Methodology: This study (Becerra & et al., 2022) assesses the impact of climate anomalies on international migration using 2013 population census data from 23,414 localities in Senegal. It also aims to examine differences in migration patterns with respect to gender, country of destination and locality or region of origin. Migrants are household members who left the country for at least 6 months over the period 2008-2013. Annual migration rates are computed at the locality level as the number of recorded migrants in a given year divided by the locality's population. They are further disaggregated by gender and destination country. Climate anomalies are measured using SPEI values from the Centre for Environmental Data Analysis (CEDA). They are computed on a 5x5km grid using CHIRPS-GlEAM data.

Results: Drier years tend to reduce international migration rates, while wetter years tend to increase them. Similar effects are found for men and women. Destination matters: the

impact is much stronger in OECD countries than in neighbouring countries, consistent with higher migration costs.

Debates, limitations and lessons learned: Similarly to the previous case study, this study illustrates both the analytical potential and the limitations of combining high-resolution climate indices with census-based migration proxies. The measure of international migration may introduce biases, such as the omission of moves by whole households and of some women's movements. Also, the retrospective approach can cover only a relatively short time span in the context of increasing precipitation. Finally, the data do not allow for the analysis of cascading effects between droughts and decreased migration to OECD countries.

Case study 10: Temporary migration response to climate variability in Senegal

Mobility patterns such as seasonal, circular, or temporary migrations clearly outweigh longer-term movements but are much more difficult to capture with traditional survey instruments. This study uses Call Detail Records over a three-year period to compute spatially detailed measures of temporary migration and to investigate the extent to which temporary migration patterns are influenced by rainy season conditions in Senegal.

Methodology: Mobile phone CDR data covering up to 12 million identifiers and about 100 billion records (calls/text messages sent or received) in 2013, 2014, and 2015 are used to detect short-term mobility responses to rainy-season conditions across harvest, off-season, and hunger periods. More precisely, migration events are detected in CDR trajectories using a clustering algorithm that identifies changes in individual users' spatial location patterns over time. Once detected, these user-level migration trajectories are aggregated to produce spatially detailed measures of temporary migration between localities, with temporary migration defined as continuous presence at a non-home location with a duration between 20 and 180 days (see (Blanchard & Rubrichi, 2025) for more details). This produces a pseudo-panel of temporary migration estimates at the (origin $*$ destination $*$ time) level, where each spatial unit of analysis is a Voronoi cell, corresponding to the area covered by a phone tower and each time unit is a "half-month". This dataset is combined with data on the quality of rainy seasons based on precipitation received from the Climate Hazard Center's CHIRPS-2.0 gridded precipitations product (Blanchard & et al., s. d.). Bilateral temporary migration rates are then regressed on rainy season conditions at both origin and destination, with origin x destination x season fixed effects included to control for (origin x destination)-specific seasonality.

Results: Precipitations at origin are found to have a positive and significant effect on the rural- rural emigration rate over the September-November harvest period following the rainy season. The relationship reverses in the subsequent off-season, from March to July. During that period, lower precipitation at the origin effectively acts as a push factor, associated with a higher emigration rate to other rural areas. On the other hand, precipitation at a rural origin has a positive effect on the rural-urban emigration rate both during the harvest period (September-November) and in the subsequent off-season, from February through May-June. Turning to conditions at the destination, lower precipitation is found to reduce the attractiveness of a rural destination during the off-season and extending into the onset of the following rainy season, from March to July, regardless of whether individuals originate from rural or urban localities. Heterogeneity analyses additionally show that the off-season, rural-to-rural response to origin conditions is relatively stronger in poorer locations with a more pronounced livestock sector.

Limitations and lessons learned: This study highlights the strong potential of mobile phone data to provide new insights into temporary migration patterns, enabling investigation of

how temporary migration responds to rainy-season conditions and how these responses vary across space and between seasons. There are, however, several potential limitations, including selection biases that may affect migration estimates, as well as complexities related to data processing and accessibility.

Conclusion

This article aimed to document, from the perspective of a collective of IRD researchers and IRD collaborators, a non-exhaustive range of conceptual and methodological frameworks applied to the study of environmental migration and (im)mobilities in the Global South. It does so at a particular moment: a third generation of researchers now works in this field, sharing a growing recognition that environmental migration and (im)mobilities cannot be reduced to simple causal chains, and that understanding it demands both conceptual depth and interdisciplinary engagement.

Each section highlights a distinct but interconnected dimension of this complexity. Part 2 shows that environmental hazards are rarely single-driver events. Compound flooding in Madagascar (Khan et al., 2025) and rainfall variability across eight countries (Afifi et al., 2016; Warner & Afifi, 2014) both illustrate the non-linear, multi-scale nature of physical drivers and the inadequacy of single-variable approaches. Part 3 demonstrated that livelihoods are more than simple economic strategies as livelihoods are historically embedded, culturally mediated practices that shape whether, how and when people move or stay, as illustrated by the Bangladesh case studies on non-migration, intergenerational resilience and livelihood diversification (Mallick et al., 2020; Mallick & Hunter, 2024). Part 4 introduced habitability as a revisited and emerging integrative concept that foregrounds the relational, political and multidimensional character of a place, capturing how environments become gradually unliveable for specific populations, and how this process is shaped by power, inequity and governance as much as by biophysical conditions (Borderon & Garcia, 2025; Garcia et al., 2025). Finally, Part 5 addressed the methodological implications of this conceptual complexity. In the first section, it presents complex adaptive systems as an overarching approach that encompasses the frameworks discussed in previous chapters (Clech et al., 2024). It also presents agent-based modelling as a tool for integrating multiple dynamics and exploring scenarios (Carles et al., 2025; Chapuis et al., 2022). Finally, in a second section, it confronts the persistent challenges of data availability, access and constraints, scale mismatch and the limits of conventional quantitative instruments (Becerra & et al., 2022; Blanchard & et al., s. d.; Defrance et al., 2023).

Across this paper, several transversal themes emerge. The first is the progressive shift from linear to complex thinking. Each framework examined shows that compound hazards, livelihoods, habitability, and complex adaptive systems contribute to dismantling the oversimplified "climate migrants or climate refugees" narrative and replacing it with a multi-causal, context-sensitive, and scale-sensitive understanding of environmental mobilities.

This conceptual evolution is neither linear nor complete: frameworks are layered, sometimes overlapping, and each carries its own disciplinary legacies and blind spots. Habitability, for instance, may help illuminate what social-ecological system frameworks leave implicit, while complex adaptive systems provide an integrative architecture that can encompass hazards, livelihoods and habitability simultaneously.

The second transversal theme is the challenge of scale. Environmental drivers operate at planetary, continental, regional, or even local scales; migration decisions are made at individual, household, or community levels; and governance operates at local, national, and international scales. Bridging these scales, both conceptually and empirically, remains one of the most pressing methodological challenges in the field. The case studies presented here range from high-resolution compound flood modelling in Madagascar to mobile phone data capturing temporary mobility in Senegal, and from ethnographic fieldwork in Bangladesh to multi-site, mixed-method surveys across eight countries. Each approach offers a partial window; none offers a complete view. This is not a failure of method, but a structural feature of complex systems research that demands plurality.

The third theme is the unfinished project of interdisciplinarity. This article documents an inspiration for integration among the environmental, social, and human sciences. Yet ecology and biology were not represented in the workshop group, reflecting how difficult this integration remains in practice. Disciplines carry different languages, temporalities, publication cultures and different epistemological assumptions. Doctoral students experience challenges when attempting interdisciplinary work in doctoral contexts designed around disciplinary norms. The COSAV structures at the IRD offer an institutional response to this challenge: a space for collective conceptual and methodological reflection across disciplinary and institutional boundaries, and this article is itself a product of that space. But much work remains to develop joint research questions and move beyond parallel contributions toward truly integrated analyses, and this is a constant work in progress.

The article is also explicit about what it does not cover. Development-induced displacement, the perspective of indigenous communities, forced displacement driven by conflict (the latter being briefly mentioned in Part 5 as a methodological illustration rather than a substantive focus) and the triple nexus environment, migration and health, will remain largely outside this work. Those omissions are not neutral; they reflect the priorities and limits of existing research communities and funding structures. Future work should actively seek to extend the frameworks presented here to these underrepresented contexts.

Looking ahead, two conceptual directions appear promising because they integrate the others. Habitability has the potential to serve as a unifying lens that holds together the material, relational, political and temporal dimensions of migration and (im)mobilities (Sterly, Borderon, Sakdapolrak, et al., 2025). Complex adaptive systems (United Nations Environment Programme, 2023; Carmichael et al., 2019; Gunderson & Holling, 2002) can serve as a representation of the system under study, a meeting point between population experience and scientific expertise, and a boundary object, a shared conceptual space flexible enough to accommodate the languages, methods and questions of multiple disciplines without erasing their differences. The habitability approach, combined with complex adaptive systems thinking, could support transdisciplinary research that neither reduces social complexity to biophysical variables nor ignores the ecological systems in which livelihoods are embedded. The UN Environment Programme's recent work provides illustrations of what such integration might look like in practice (United Nations Environment Programme, 2023).

More fundamentally, this article argues, implicitly through its case studies and explicitly through its conceptual discussions, that environmental migration and mobility cannot be adequately understood without a critical reflection on the global political economy that shapes them. Environmental degradation is not distributed randomly; it bears most heavily on populations in the Global South who have contributed least to its causes.

Mobilities are not simply adaptive responses to environmental change. For many populations, including traditionally nomadic, pastoralist, and indigenous communities, as well as some rural and coastal traditions, movement is a constitutive livelihood practice and a culturally embedded right, not a reaction to crisis. Yet, for all, environmental migration and (im)mobilities are shaped by structural inequalities, constrained by legal and political frameworks, and marked by colonial and postcolonial relations that continue to determine whose knowledge counts, whose movement is protected, and whose traditional mobilities are criminalised or erased. Research on environmental migration must therefore be not only interdisciplinary but also reflexive, aware of the knowledge hierarchies it reproduces, and committed to approaches that centre the perspectives and agency of the populations most affected.

Finally, this article is the product of a collective reflection initiated during a workshop in autumn 2024. It is also unfinished; the questions it raises will be pursued further during an autumn school, planned for autumn 2026.

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