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Aspirations in a warming world: Modeling migration and education decisions under climate risk in Senegal

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ABSTRACT

The ability to project migration flows is important to government planners at multiple scales as they balance challenging tradeoffs in social infrastructure investments amid changing populations and escalating climate risks. Simulation methods such as agent-based modeling have generated important insights about the non-linear ways in which climate shocks may reshape migration decision-making processes. However, these approaches have previously demonstrated limited ability to account for how climate risks may shape migration decisions through changes to individuals' long-term livelihood aspirations. Here, we develop an agent-based model of livelihood decisions in Senegal, one of Africa's fastest-growing populations and economies, in which human capital investments – including migration and post-secondary education – emerge endogenously from agents' dynamic livelihood aspirations. In doing so, we incorporate theoretical insights from the migration aspirations-capabilities framework to simulate how individuals weigh near-term investments against long-term opportunities. In collaboration with migration and development experts, we apply the model to assess how two of West Africa's most significant climate risks, droughts and sea level rise, influence human capital investments at individual, regional, and national scales. We find that climate shocks alter both the timing and nature of human capital investments and shift population distributions. Notably, an interior crescent that has not typically served as a migration destination – including the departments of Podor, Nio du Rop, Sedhiou, and Kolda – emerges as a key safety corridor for migrants from climate-vulnerable coastal and rural zones. Further, we find that migration and access to higher education significantly improve resilience to short- and medium-term climate shocks, increasing individual incomes by 40 to 250 percent across different scenarios. Our findings demonstrate the value of integrating a livelihood aspirations framework with modeling tools to understand the long-term consequences of climate shocks on migration and economic outcomes. These insights can inform targeted investments in improved access to education and mobility to build resilience to these shocks.

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1. Introduction

In many emerging economies, mobility has long formed an important component of household livelihood strategies. For example, farmers may migrate seasonally to supplement uncertain agricultural incomes (Millock, 2015; Salerno, 2016); youth may migrate to urban areas to pursue education, employment, and/or fulfill social expectations (Williams, 2009; Prothmann, 2018); and entire households may move temporarily or permanently in response to natural disasters (Bohra-Mishra et al., 2014). Climate change adds complexity to these traditional migration motivations by altering seasonal weather patterns that have previously shaped migration patterns (Lalou and Delaunay, 2017) and increasing the frequency and severity of extreme events (Intergovernmental Panel on Climate Change, 2012). At a global scale, climate-driven hazards are projected to induce between 44 million and 216 million additional people to migrate by 2050 (Clement et al., 2021), while climate-induced income losses may simultaneously constrain mobility options for vulnerable populations (Black et al., 2013; Benveniste et al., 2022). At finer scales, climate change intersects with various forms of financial, social, political, and human capital in complex ways, resulting in diverse migration responses to evolving climate risks (Black et al., 2013; Nawrotzki and DeWaard, 2017; Lutz and Muttarak, 2017; Benveniste et al., 2025).

The ability to project migration flows at multiple geographic and temporal scales is important for informing several policy processes, including housing and urban development, economic development, and public educational and health investments. The diversity of migration responses to climate forcings makes agent-based modeling an especially relevant method to inform such processes. Agent-based models (ABMs) simulate interactions between heterogeneous decision-makers ("agents", which can represent individuals, households, and/or communities) as they make adaptive strategy decisions under evolving conditions. In the climate migration field, ABMs have demonstrated complex responses to various climate-driven hazards, including: simultaneous outflows and inflows in areas affected by sea level rise (Bell et al., 2021); immobility in response to gradually worsening crop yields (Choquette-Levy et al., 2021); and divergent migration responses within a population exposed to climate shocks based on heterogeneous adaptive capacity (Entwisle et al., 2016). Yet, these models typically represent migration decision-making as an agent's assessment of contemporaneous livelihood options at a given time. As such, they may not fully capture how varied perceptions of current and future climatic conditions may shape long-term livelihood aspirations, which are an important component of migration decisions (Black et al., 2022).

One relevant theory for linking current migration behavior with future livelihood goals is the "aspirations-capabilities" framework (de Haas, 2021; Carling, 2002), which embeds migration as an act that results from the interplay between individuals' life aspirations and current set of capabilities. This framework posits that aspirations are dynamic throughout the life course and may change as a function of evolving social networks, information, and education. As part of these changing aspirations, an individual may intend to migrate for inherent purposes (e.g., to fulfill a sense of wanderlust or comply with social norms of migration) and/or functional purposes (e.g., to achieve educational, economic, or social goals). Individuals' capabilities are shaped by their own personal capitals (including financial, physical, social, and human), as well as dynamic political, social, and economic institutions. Such factors may affect both positive liberty (i.e., ability to proactively engage in an activity) and negative liberty (i.e., freedom from restrictions on pursuing an activity), including whether and how individuals can engage in migration (Berlin, 1969; Sen, 1999). This theoretical framework offers promise for better representing underappreciated mechanisms through which climate change may affect migration decisions through a long-term restructuring of livelihood aspirations.

This study contributes to an increasingly nuanced understanding of migration as a climate adaptation strategy (Sakdapolrak et al., 2016) by representing migration aspirations in a model of livelihood decision-making. Specifically, we develop an ABM of individual livelihood decision-making in which agents choose locations and economic activities based on envisioned livelihood trajectories that are informed by their long-term aspirations. When gaps exist between agents' aspirations and current livelihood capabilities, this may motivate human capital investments (represented here as migration, higher education, and/or acquiring experience in a particular livelihood) to eventually achieve the aspiration. These investments thus arise endogenously from the interplay of dynamic aspirations and capabilities. We apply this model to a case study of short- and long-term climate risks in Senegal, a country with high climate vulnerability (University of Notre Dame, 2026; World Bank Group, 2024), a large youth population, and a long tradition of both internal and international forms of migration as livelihood strategies (Prothmann, 2018; Lalou and Delaunay, 2017; Romankiewicz and Doevenspeck, 2015; Ribot et al., 2020; Diallo, 2024). Our case study is further motivated by a strong domestic and international policy focus on managing high migration rates through investments in rural vocational schools and the trades sector, based on the assumption that improved access to these forms of human capital will dampen migration aspirations (République du Sénégal, 2024; International Organization for Migration, 2007). Senegal therefore represents a most-likely case study (Eckstein, 2009); if there are mechanisms by which climate change affects livelihood aspirations, in turn modifying migration decisions, we would expect to find it in such a setting.

Informed by a participatory stakeholder modeling process, we adapt an existing ABM called the Migration, Intensification, and Diversification as Adaptive Strategies (MIDAS) (Bell et al., 2019, 2021) to address the following locally relevant research questions:

1. *To what extent can embedding an aspirations framework into an ABM generate new insights on migration processes?*
2. *Accounting for dynamic livelihood aspirations, how do different climate shocks affect the nature and timing of individual decisions regarding migration and post-secondary education in a heterogeneous population and economic landscape?*

For reasons of parsimony, data availability, and policy relevance to our case study, we restrict our analysis to internal migration flows and formal post-secondary education within Senegal. However, our modeling approach provides a generalizable framework to endogenize other forms of human capital investments – including healthcare, primary and secondary education, apprenticeships, and international migration (Abraham and Mallatt, 2022) – as a function of agents' dynamic aspirations and capabilities, which are shaped by heterogeneous exposure to information, resources, and climate-related shocks.

In Section 2, we describe the conceptual model and theoretical groundings for this modeling approach. Section 3 then describes our participatory modeling approach, model development, key data sources, and the climate change scenarios through which we analyze the model. Section 4 presents the results from these scenarios, investigating how different shocks re-shape migration patterns, educational investments, and economic outcomes at national, regional, and individual scales. Finally, we conclude in Section 5 with a discussion of the analytical contributions of endogenizing an aspirations framework in ABMs, and hypotheses emerging from our modeling analysis that warrant further empirical study.

2. Conceptual model

Advances in empirical research and computational modeling have generated many insights about the varied ways in which the environment shapes migration decision-making. In the 1980s and 1990s,

scholarship first drew attention to environmental hazards, including droughts and pollution, as important migration "push" factors that may drive individuals and communities to leave increasingly inhospitable places (El-Hinnawi, 1985; Findley, 1994). Scholars subsequently situated environmental factors as one of several categories of migration drivers, exploring their interactions with economic, social, and political factors (Foresight, 2011; McLeman, 2014; Hunter and Simon, 2023). Over the past two decades, analysis of climate-migration case studies has grown exponentially (Piguet, 2022), contributing to a nuanced understanding of the plurality of migration responses to environmental change. For example, Nawrotzki et al. demonstrated that social networks may amplify an initial out-migration response to weather shocks through successive migration waves (Nawrotzki et al., 2014). Other scholars demonstrate that the interaction between restrictive border policies and weather shocks may drive increased irregular migration (Cottier and Salehyan, 2021). Critically, recent demographic work has shown that populations often exhibit heterogeneous responses to the same environmental pressures, driven by differential perceptions and adaptive capacity to such changes (Lutz and Muttarak, 2017; Muttarak and Lutz, 2014). One increasingly observed response is immobility – the process by which climate and/or environmental stress impedes an individual or sub-population from migrating by constraining their ability to do so Black et al. (2013), Choquette-Levy et al. (2021) and Benveniste et al. (2022).

While these findings have already contributed substantially to migration theory (Hunter and Simon, 2023), critical gaps remain in updating theoretical frameworks to account for multi-faceted and dynamic migration responses to climate change (de Sherbinin et al., 2022). In particular, understanding how diverse populations perceive their changing environments, how climatic factors affect alternatives to migration, and how various forms of mobilities contribute to climate resilience remain open for theoretical development (Piguet, 2022; de Sherbinin et al., 2022; Garcia et al., 2025). The aspirations-capabilities framework offers a useful conceptual bridge in this regard by elaborating multiple pathways through which climate change may impact migration decision-making. Specifically, it posits that migration decisions arise from evolving aspirations – factors that shape the desire to migrate – and capabilities – factors that affect the ability to migrate. Aspirations may be shaped by instrumental motivations such as the desire to increase income and seek new livelihood opportunities, but also by intrinsic motivations such as wanderlust and the fulfillment of social and gender norms. Similarly, capabilities refer to the set of financial, social, human, and cultural capitals that allow for migration, and the political and institutional contexts that condition whether and how someone can move. Subsequent work has theorized that gaps between economic aspirations and current capabilities motivate individual human capital investments to achieve a desired state (Genicot and Ray, 2017), which could include migration, formal education, and/or non-formal types of training. In this framework, climate hazards may shape migration decisions not only by altering near-term livelihood capabilities, but also the return on human capital investments and the future livelihood aspirations that motivate such investments (Fig. 1).

Agent-based models (ABMs) are especially useful in systematically investigating the role of aspirations in mediating the climate-migration relationship. Because ABMs allow for dynamic, adaptive behavior among heterogeneous agents, they can be used to analyze how an environmental or climate shock may affect livelihood aspirations differently in a diverse population, and how such modified aspirations produce a range of migration responses over time (Klabunde and Willekens, 2016). For example, ABMs can be used to track lagged responses between the occurrence of an environmental hazard, perceptions of its timing and severity, shifts in long-term livelihood aspirations, and adaptations to near-term investments to fulfill such aspirations. ABMs can simultaneously assess important dimensions of heterogeneity within a population at each of these steps, as well as the moderating effect of other *in situ* livelihood opportunities (e.g., agricultural, vocational, professional, and educational activities) on how a climate shock affects migration decision-making. However, previous ABMs generally model individuals' and households' short-term responses to changing social and environmental conditions, rather than allowing agents to proactively consider multiple sequential steps along their life course pathway. This approach neglects mechanisms through which an agent may perceive climate change to materially affect the long-term viability of their envisioned livelihood pathways, triggering shifts in near-term investments (Fig. 1, blue lines). Underrepresenting this aspect of decision-making may impede such models' ability to accurately project migration and other livelihood responses to environmental shocks over longer time scales.

Here, we develop a novel framework for analyzing how environmental change dynamically affects migration aspirations and behavior via an existing ABM of livelihood decision-making, MIDAS (Migration, Intensification, and Diversification as Adaptive Strategies). MIDAS agents represent individuals with different age, sex, and behavioral characteristics (e.g., risk aversion, loss aversion, time discounting) who make decisions in each model time step about the set of livelihoods they wish to pursue. Livelihoods are represented as sets of economic activities – including the agriculture, trades, professional, and service sectors – that differ over space and time. MIDAS is spatially and temporally explicit, such that each region in the model is characterized by livelihood activities with place- and time-dependent utilities, reflecting real-world wage differentials and dynamic processes such as congestion effects and heterogeneous climatic impacts (Millock, 2015). Migration decisions arise endogenously when agents perceive livelihoods that are more attractive in other locations, either due to better wages or a lack of similar opportunities in their current location, subject to migration cost constraints. Several types of migration behavior emerge based on agents' evolving perceptions and resources, including short-term, cyclical, and long-duration migration.

In this study, we add a mechanism through which climate-driven hazards may affect human capital investment decisions by modifying livelihood aspirations. Specifically, we develop a framework for agents to consider future livelihood aspirations (e.g., working in a professional job in a city) that may not necessarily be available to them yet. Livelihood aspirations may require specific pre-requisites for agents to access them (e.g., a certain number of years of formal education, informal experience, and/or living in a particular area). When gaps exist between an agent's current capabilities and future livelihood aspirations, this may motivate the agent to invest in near-term human capital to accumulate these pre-requisites, subject to financial, informational, and geographical constraints. We add two types of post-secondary educational opportunities (two-year vocational training and four-year university degrees) in this application of MIDAS. These processes are further described in Section 3.3.

While this work is inspired by the aspirations-capabilities theory, for reasons of computational tractability and interpretability, we only engage with a limited portion of this expansive framework: specifically, we analyze how environmental change affects economic components of migration aspirations and shapes financial, social, and informational capitals that condition migration capabilities. We note that future iterations of this modeling approach could engage with additional components of this framework, including intrinsic motivations for migration and other forms of positive and negative liberty that affect migration capabilities. Our approach also extends the aspirations-capabilities framework by embedding migration decisions within a broader set of human capital investments that are motivated by distinct livelihood aspirations. This allows us to investigate how climatic shocks to different regions and economic sectors may produce different migration and post-secondary educational decisions. In doing so, we seek to demonstrate how this type of migration modeling can generate important insights for policy-relevant questions regarding the intersection of climate, migration, and human capital investments.

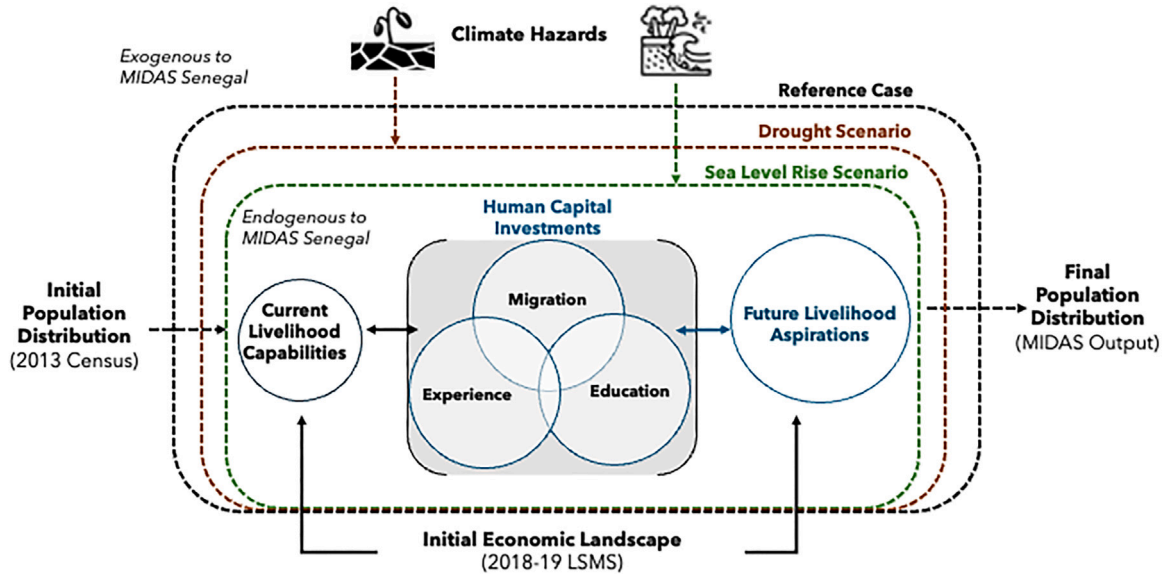

Fig. 1. Conceptual diagram of climate impacts on livelihood capabilities, human capital investments, and aspirations. Our conceptual model embeds human capital decisions – including migration, formal education, and informal experience – as a link between individuals' current livelihood capabilities and future livelihood aspirations. Generally, such investments grow the livelihood options available to individuals over time. Current scholarship focuses primarily on climate impacts to current capabilities and returns to human capital investments. We seek to add the dimension of climate impacts to livelihood aspirations, and the human capital investments they motivate, as another pathway through which climate may shape migration and education decisions. In this study, we compare such decisions under two scenarios of climate-driven hazards, drought and sea level rise, against a stationary climate Reference Case. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Data and methods

In this section, we describe the participatory process that informed our model development, modifications we made to incorporate an aspirations framework into MIDAS, steps taken to calibrate MIDAS to our Senegal case study, and scenarios we constructed with our modeling partners to investigate policy-relevant questions of environmental change, migration, and human capital investments.

3.1. Participatory modeling approach

Participatory modeling is a transdisciplinary approach that "engages the implicit and explicit knowledge of stakeholders to create formalized and shared representations of reality" (Voinov et al., 2018). Such participatory processes can take several forms, ranging from in-depth co-construction of research questions with communities to occasional informational sessions with decision-makers to disseminate results of a research project (Zellner, 2024; Hedelin et al., 2021). In this project, we opted for a medium-engagement participatory process by convening a series of in-person and online workshops with migration policymaking and academic professionals (participating organizations are listed in the Supplementary Information, Section 1). Our primary objective in engaging this set of stakeholders was to adapt MIDAS so that it can inform policy-relevant questions regarding migration and development under environmental change in Senegal. While we did not directly engage with rural Senegalese communities due to limited capacity, this process provided a channel for both Senegalese and international practitioners to bring their grounded insights on migration drivers in the region, and their higher-level perspectives on relevant policy developments for our case study.

Participants highlighted several factors that make Senegal an especially important case study for investigating such questions. First, it is a country with a long tradition of both internal and international migration, shaped in part by insecurity of subsistence livelihoods and a lack of local formal employment opportunities (Lalou and Delaunay, 2017; Ribot et al., 2020). Although Senegal has a relatively well-developed system of universities compared to many of its neighbors, practitioners noted that graduates of these universities still face significant challenges in obtaining secure employment, as international degrees are often preferred by employers. Consequently, recent domestic and international policy has sought to counter high migration rates by investing in rural economic development, especially through the formation of trade schools in each of the country's eight major regions (République du Sénégal, 2024; International Organization for Migration, 2007). Yet, it is still unclear how such investments will reshape livelihood aspirations, including the desire to migrate. Participants noted that multiple climate risks to livelihoods – including drought and desertification in the rural interior and sea level rise along the more developed coastal regions – provide a new dimension of uncertainty to livelihood aspirations and migration decisions. For these reasons, Senegal represents an especially important case study for the application of an ABM to investigate how climate change shapes livelihood aspirations and human capital investments, as it may offer insights relevant to several climatological and development contexts across West Africa and the Global South.

Our first workshop, held in person in Dakar, focused on identifying key questions of interest and decision-making processes that participants felt were important for the model to capture in order to inform those questions. The online engagements that followed were designed to (i) help team members develop shared understandings of how concepts were operationalized in our model application; (ii) continue refining experiments to best test our questions of interest; and (iii) interpret the outputs from our model experiments. A core team of stakeholders consistently engaged in this process through all three phases, some left the process at various points due to time constraints, and others joined as we further developed our networks (SI Table 1). While these transitions presented some challenges in integrating newer participants in an ongoing model development process, they also contributed new perspectives that had not been previously discussed in earlier stages. Specific stakeholder contributions included: identifying specific mechanisms that shape Senegalese aspirations and capabilities, including the emerging role of vocational schools; prioritizing model outcomes against which to calibrate this model application to the Senegal case study (Section 3.4); and developing environmental change

scenarios that reflected the most pressing concerns for this case study (Section 3.5).

3.2. Model description and data sources

To adapt MIDAS to the Senegal case study, we parameterized six livelihood categories that broadly represent economic activities available in agriculturally-dependent societies: agriculture and aquaculture, livestock, professional jobs, services, small businesses, and trades. Specific incomes generated from each livelihood vary spatially and temporally. For example, income from agriculture is generally higher in more fertile regions and/or in years with favorable weather, and lower in regions with more marginal soils and/or in years with less favorable climate. In each time step, agents make livelihood and location decisions that maximize their utility, subject to a few constraints. First, each livelihood activity is associated with a set amount of labor the agent must devote to it, limiting the amount of activities an agent can pursue simultaneously. Second, emulating bounded rationality (Simon, 1972), agents do not have perfect information on incomes available from all possible livelihood activities in each location, and are limited to comparing the utility of their current livelihood portfolio against a limited set of alternative locations and livelihood portfolios. These alternatives arise from portfolios agents have recently considered and livelihood opportunities that they have heard about from their social connections (in this application of MIDAS, agents consider up to six alternative locations and four livelihood portfolios per location, SI Table 4). Third, agents entering into new livelihood activities must accumulate sufficient financial resources, and in some cases experience and/or formalized training (Section 3.4). While such constraints may limit the choices agents can make in any given time step, an agent's information, financial resources, and training evolve as a function of their decisions, leading to dynamic livelihood choices over time. Agents update their information and re-evaluate decisions in time steps representing three months, allowing them to adjust how they employ their time based on seasonal patterns, such as planting and harvesting seasons that require more agricultural labor. For this analysis, we run a simulation for 100 time steps, representing a 25-year timeframe starting in the year 2020, and run 30 simulations per scenario to account for stochasticity in agents' exposure to new information. For more information on the basic structure of MIDAS, please consult the SI, Section 2, and the MIDAS Overview, Design concepts, and Detail Appendix in Bell et al. (2019).

3.3. Endogenizing an aspirations framework

A key modeling advancement presented in this paper is the endogenization of aspirations and human capital investment decisions in a migration ABM. To emulate economic returns to varied human capital investments, some income-generating activities in this application of MIDAS can only be accessed upon completion of a specified amount of training and investment in a prerequisite livelihood layer. For a given agent and time period, we designate the set of livelihood activities that are not yet accessible but that could be enabled by human capital investments as potential aspirations. To represent how agents may factor such aspirations in their decision-making, we consider two temporal components of the agent's utility function: an initial utility from a near-term set of activities that an agent can currently deploy at a given time and place (henceforth referred to as the "high-fidelity" component of an agent's livelihood pathway), and a second set of future activities that include an aspiration requiring additional training, experience, and/or financial resources. For example, an agent representing a young, male rural Senegalese adult may wish to work in the trades or professional sector in a more urban location – this represents the agent's long-term aspiration (Fig. 2). To achieve this aspiration, the agent considers near-term livelihood portfolios that include attending vocational school in a nearby location (a prerequisite) while farming part-time over the next two years – this would represent the agent's near-term, high-fidelity pathway.

Mathematically, we represent this as:

$$U_{isl} = \sum_{t=1}^{t=\tau} \frac{U_{il}^{H}(t)}{(1+r)^{t}} + \sum_{t=\tau+1}^{t=h} \frac{\bar{U}_{i}^{A}(t)}{(1+r)^{t}} \quad (1)$$

with $\bar{U}_{i}^{A}(t)$ calculated as:

$$\bar{U}_{i}^{A}(t) = \frac{1}{K} \sum_{k=1}^{K} U_{i,k}(t) \quad (2)$$

where U_{isl} represents the total net present value of utility for agent i in time period s and location l for a given livelihood pathway; $U_{il}^{H}(t)$ and $\bar{U}_{i}^{A}(t)$ represent the utilities of high-fidelity portfolio and average utilities of the low-fidelity aspiration, respectively, of agent i in time period t; τ represents the duration of agent i's high-fidelity portfolio and h the total time horizon over which i evaluates livelihood pathways; and r the discount rate. The low-fidelity portion of an agent's livelihood portfolio, $\bar{U}_{i}^{A}(t)$, represents an average utility from K potential portfolios across different locations that include an agent's aspiration (here, we set $K = 100$ potential portfolios to capture a wide variety of potential livelihood pathways and locations that the agent could consider). In this formulation, agents' evaluations of various livelihood options are thus determined by the net present value of the near-term utility they can derive from the high-fidelity portfolio (in our example, income from farming and a vocational school stipend) and the longer-term utility of aspirations that would be enabled by the near-term portfolio (in this example, a composite of potential incomes from the trades sector in different departments). This provides a consistent framework for representing real-world decision-making in which individuals may consciously plan life course paths over several years, and must evaluate the near-term and longer-term costs and benefits of these paths with varying levels of precision.

3.4. Model calibration

To adapt MIDAS to our case study in Senegal, we parameterize economic parameters based on the 2018–2019 Senegal Living Standards and Measurements Survey (LSMS) (WAEMU Commission, 2018–2019), a nationally representative survey of livelihoods, welfare, and smallholder agriculture. Among other data, the LSMS reports respondents' gender, household income, employment, and geographic region, which we aggregate into six economic categories (agriculture-aquaculture, livestock, professional occupations, service-based occupations, trades, and small businesses), 45 Senegalese departments (a Level 2 administrative unit), and two genders. We also add a seventh livelihood category – post-secondary education – which we represent as two levels: a 2-year vocational training pathway and a 4-year university pathway. Based on input from our stakeholder group, we parameterize each educational pathway with a small stipend of 100,000 CFA/year (approximately 150 USD). Agents residing in locations without a post-secondary university or vocational school must first migrate to a department with the appropriate institution if they wish to pursue one of these pathways (see SI 1.3 for a list of such departments). The geographic distribution of agents in this application of MIDAS is parameterized based on the proportion of the Senegalese population in each department according to the 2013 National Household Census (Boyle et al., 2019).

We calibrate remaining uncertain parameters (e.g., agent risk aversion, number of social connections, etc.) by generating 1000 simulations of MIDAS, taking uniform random draws from the parameter ranges specified in SI Table 2. Simulated results are compared against a set of six empirically observed metrics from the LSMS and National Household Census prioritized by our stakeholder group: (1) the overall proportion of the population that migrates; (2) the migration flows between eight Administrative 1 Senegalese regions (each of which aggregates 3–4 Administrative 2 departments); (3) the proportion of migrants that are female; (4) the proportion of all migrants that go

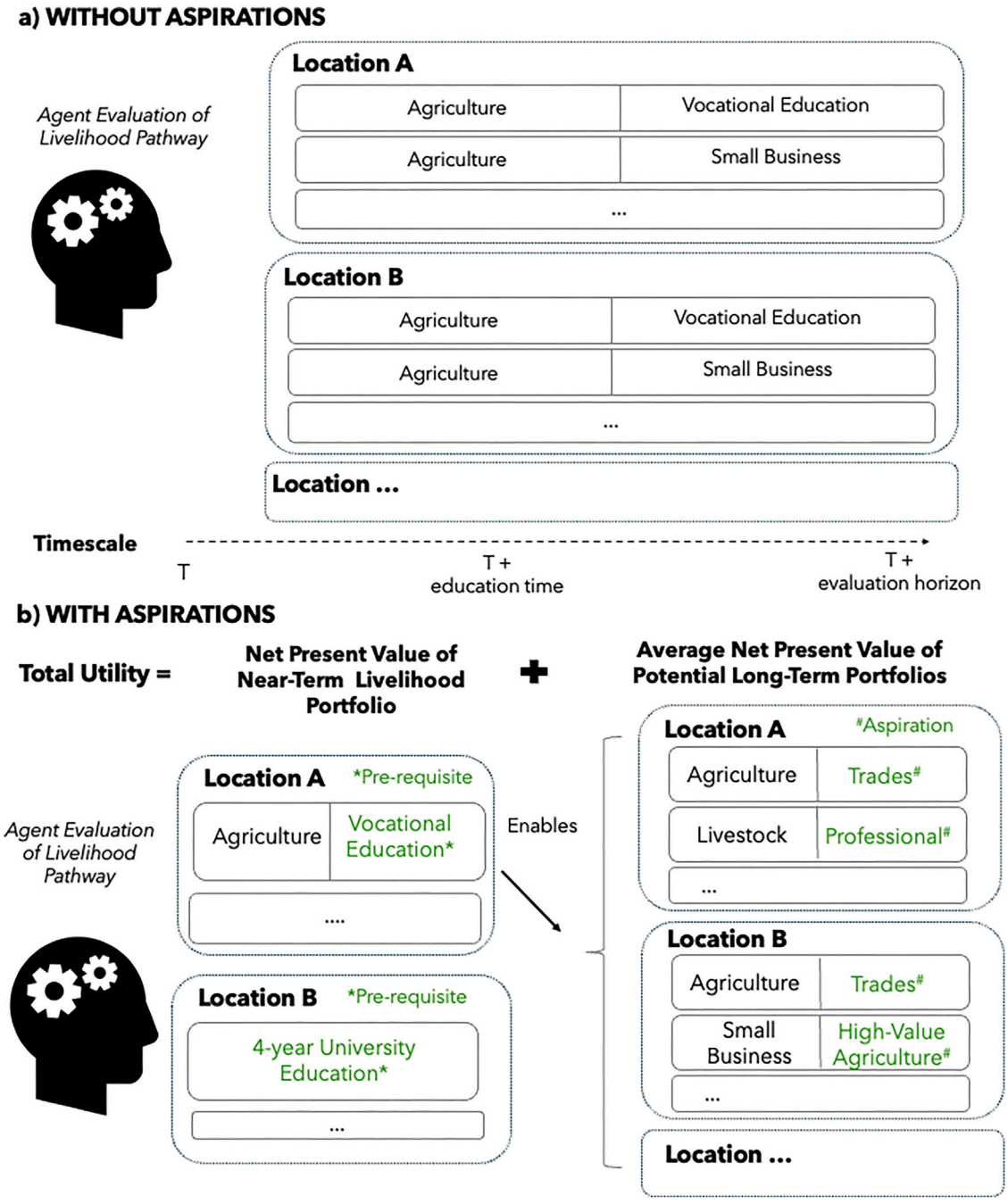

Fig. 2. MIDAS agent's perspective on livelihood utilities. In MIDAS Senegal, agents evaluate the utility of potential livelihood "pathways" of connected activities over multiple time scales. Any given pathway consists of a specific set of activities in a specific location (e.g., agriculture and vocational education in Location A). Agents may evaluate different pathways in a given location, as well as pathways available in different locations, subject to informational constraints. **(a)** Without endogenized aspirations (i.e., the default in most ABMs), agents evaluate the utilities of different sets of static livelihood pathways over their entire evaluation time horizon (representing 10 years in this MIDAS application). **(b)** With aspirations (i.e., the modeling advancement in this study), agents evaluate the combined utility of near-term portfolios they can currently pursue, as well as sets of future activities that could be enabled after sufficient human capital investment (e.g., working in agriculture and trades in Location A, opening a small business and working in trades in Location B, etc.). The utility of the full pathway is evaluated as the net present value of the near-term livelihood portfolio and the average net present value of possible future portfolios.

to Dakar; (5) the distribution of employment in each Senegalese region across six economic sectors; and (6) the proportion of people in each economic sector with post-secondary education. In conjunction with the group, we selected a set of Reference Case parameters that performs relatively well across the six metrics, rather than optimizing for performance against one single metric. This set of parameters generally performs well in replicating multiple migration patterns and post-secondary educational attainment, though it does not perform particularly well in reproducing the share of migrants that go to Dakar or the distribution of agents by economic sector. This may be because there are additional non-economic factors drawing migrants to the Senegalese capital – including cultural and marriage pull factors – as well as informal economic activities that are not well-represented in MIDAS. Nevertheless, as this combination performs well in replicating

overall migration and education decisions – the main focus of our analysis – we use this combination as our Reference Case.

3.5. Model scenarios

To systematically assess how endogenizing aspirations may affect projections of migration under different types of climate-driven shocks, we co-developed a set of three main scenarios with our practitioner group. First, we develop a Reference Case Scenario that projects the current distribution of livelihood opportunities (as measured by the 2018–19 LSMS) into the next 25 years under stationary climatic conditions. While we do not expect this to actually reflect future environmental and economic conditions, it serves as a useful model baseline in order to isolate the effects of different climatic shocks that we subsequently impose. In our series of workshops, participants identified two types of climatic hazards that were assessed to be high-priority scenarios for this analysis: a multi-year drought in the interior Senegal River Valley, and chronic sea level rise along the coastal Atlantic regions. These scenarios are instructive for climatic, geographic, and demographic motivations. From a climatic perspective, the 2023 Intergovernmental Panel on Climate Change Assessment Report identifies droughts and sea-level rise as the two most important climate-driven risks facing West Africa (Trisos et al., 2022). Specifically, droughts in this region are projected to become more frequent and severe, threatening agricultural livelihoods and freshwater resources (Trisos et al., 2022; World Bank Group, 2022); sea levels along West African coasts are projected to increase by 0.3–0.8 m over the 21st century, driving increased flooding, erosion, and saltwater intrusion risks along heavily-populated coastal areas (degli Uberti et al., 2021; World Bank Group: Climate Change Knowledge Portal, 2021). Our group was therefore motivated to better understand the implications of these climatic threats for human capital decisions in the Senegalese context.

From a geographic and demographic perspective, these hazards also affect two substantially different regions and populations within the country. Droughts are a particular threat for the interior Senegal River Valley (including regions such as Podor, Matam, and Tambacounda), an area dominated by informal, agriculture-based livelihoods where seasonal and permanent migration have long played important roles as risk management strategies (degli Uberti et al., 2021; Ribot et al., 2020; Lalou and Delaunay, 2017). This region has also been characterized as a "moral economy", in which strong family, gender, community, and religious norms impose substantial pressures on young adults to migrate (Deslauriers et al., 2022; Petit, 2018). By contrast, sea level rise is a particular threat for Senegal's urban coastal regions (e.g., Saint-Louis, Dakar, and Thiés), where the country's urban development, universities, and formal employment opportunities are concentrated (degli Uberti et al., 2021; Romankiewicz and Doevenspeck, 2015; World Bank Group, 2024). These regions have traditionally served as destinations for seasonal and permanent migrants from the country's interior, as well as transit points for migrants seeking international destinations (Prothmann, 2018; degli Uberti et al., 2021). Our group therefore prioritized understanding how climate risks to each of these regions, representing opposite ends of the development spectrum in the country, may directly and indirectly affect human capital decisions.

We describe each of the three main scenarios (Reference Case, Senegal River Valley Drought, and Sea Level Rise) in more detail below.

- **Reference Case Scenario.** In the Reference Case Scenario, we assume that the current geographic distribution of educational opportunities and economic opportunities (as of 2018–19) remains fixed, and allow agents to make educational, livelihood, and migration decisions based on this distribution. Each realization of the Base Case employs a different draw of incomes for each livelihood and department, but these remain stationary throughout the model timeframe. Dynamic agent behavior results from agents accumulating or losing financial resources due to changes in livelihood activities and investments, learning about new livelihood opportunities from their social networks, and congestion effects that reduce utilities from crowded sectors and locations. This scenario serves as a baseline for how migration patterns and livelihood decisions may evolve under a stationary climate and policy environment. We also model a No Aspirations baseline case, which allos us to isolate the effects of endogenized aspirations on projected migration behavior.[1]
- **Climate Scenario 1: Senegal River Valley Drought.** Our first climate scenario investigates the impacts of a multi-year, time-bound shock due to a regional drought on livelihood aspirations and decision-making. In several instances over the past few decades, drought has afflicted farmland along the Senegal River Valley (stretching from the northwest corner of Senegal, near St-Louis, to the southeast corner in Saraya). Here, we explore the effects of a potential five-year mega-drought in the region that directly affects the agricultural sector through decreased yields and diminished economic opportunities in non-agricultural sectors. In the main specification, we impose a 50 percent reduction in agricultural sector income in departments bordering the Senegal River. This loss accords with modeled impacts of a 50 percent decrease in precipitation and 2.5–5 °C increase in temperature on maize yields in Senegal (Setti et al., 2023). It is also in line with a reported 59 percent loss in nation-wide groundnut yields in 2011 due to drought conditions (Diallo, 2024). To capture the economy-wide spillover effects of drought, we also model a 30 percent reduction in the income potential of non-agricultural sectors in this region, based on the ratio of agricultural vs non-agricultural income losses reported from natural disasters in Bangladesh (Mueller and Quisumbing, 2011). As any particular drought may have variable impacts on both agricultural and non-agricultural incomes, we also conduct a sensitivity analysis of different levels of drought severity on agent livelihood decisions (SI Section 3).
- **Climate Scenario 2: Saltwater Intrusion along the Atlantic Coast.** Our second climate scenario explores the effects of rising global sea levels, depleting groundwater aquifers, and increased salinity along coastal regions. Under most Shared Socioeconomic Projections, sea levels along the Senegal Atlantic Coast are expected to increase by an average of at least 0.25 m by 2050 (World Bank Group: Climate Change Knowledge Portal, 2021), exacerbating the salinity issues with which farmers in coastal Senegalese regions are already contending. This scenario models the effects of slow-onset sea level rise (SLR) along the Senegal coastal floodplain (Open Street Map, 2025) by gradually reducing the income that can be earned from all livelihoods in affected departments. Specifically, we model a linear 90 percent decline in agricultural and aquaculture incomes from their original levels by the end of the model timeframe, matching crop yield declines that farmers in regions affected by saltwater intrusion have already observed (Thiam et al., 2019). To capture the wide-ranging effects of SLR on non-agricultural sectors, including the effects of erosion and floods on physical infrastructure (Roy et al., 2022), we also model a gradual 45 percent decline in non-agricultural income over the same time period. Thus, in each year, agricultural/aquaculture-based livelihoods see a decrease of 3.6 percent of their original value, and other sectors see a decline of 1.8 percent of their original value. To explore uncertainty regarding the pace of global sea level rise and its relation to saltwater intrusion, we conduct a sensitivity analysis of the severity of this decline (SI Section 5).

[1] In the versions without aspirations, Eq. (1) is adjusted to $U_{i,s} = \sum_{t=1}^{t=h} \frac{U_i^H(t)}{(1+r)^t}$, such that the agent only considers a currently-accessible high-fidelity portfolio. The net present value of this portfolio is evaluated for the agent's entire decision horizon, h.

4. Results

In this section, we present results from our analysis at individual and population scales. First, we demonstrate the value of incorporating aspirations in a migration ABM by comparing results from our Reference Case, with and without aspirations. We then analyze how the drought and saltwater intrusion scenarios affect livelihood decision-making in our model, including human capital investments in migration and education. Finally, we examine how differences in agent livelihood decision-making under these scenarios lead to different long-term population distributions in Senegal.

4.1. Effect of incorporating aspirations

Our first research question concerns whether incorporating an aspirations framework in a migration ABM allows for a richer representation of agents' human capital investment decisions. We evaluate this question by comparing results from our Reference Case to a No Aspirations Scenario, which removes agents' ability to form aspirations while keeping all other model factors equivalent to the Reference Case. Across both scenarios, migration rates steadily increase in the first few years of the modeled timeframe as agents adjust to geographic disparities in livelihood opportunities, before reaching a steady state around Year 12. In the No Aspirations Scenario, a mean of 5.3 percent of agents per year engage in internal migration by this time (Fig. 3a, blue shaded region).[2] By contrast, in the Reference Case, a mean of 7.7 percent of agents engage in migration per year by Year 12, representing a 45 percent increase from the No Aspirations Scenario. Furthermore, fewer agents in the No Aspirations Scenario obtain post-secondary education by the end of the modeled timeframe — only 18 percent of agents receive vocational and/or 4-year university training, compared to 44.3 percent of agents in the Reference Case Scenario (Fig. 3c). In further results (SI Section 3), we demonstrate that accounting for aspirations in the Reference Case also lowers the female proportion of migrants and post-secondary graduates, likely reflecting more limited long-term economic pathways for women in this context. Although the migration and post-secondary education rates at the end of the modeled timeframe in the Reference Case are significantly higher than those in the 2013 Senegal Census, it is plausible that these rates continue to rise over the next 25 years as a function of economic development. Importantly, each of these patterns matches our intuition — without the ability to proactively compute how short-term human capital investments may lead to future livelihood opportunities, agents in the No Aspirations Scenario are substantially less likely to migrate and/or pursue higher education.

The effects of restricting agents' capacities to form aspirations lead to several economic implications. For example, in the No Aspirations Scenario, mean agent incomes rise from 240,000 to 483,000 CFA/year (in 2018 real CFAs, or 432 to 869 2018 USD) by the end of the model simulation, representing a compound annual growth rate of 3.16 percent, whereas in the Reference Case mean incomes rise from 240,000 to 631,000 CFAs/year (1140 USD/year) in the same timeframe, representing a 4.39 compound annual growth rate. Allowing for aspiration formation allows us to better approximate the average annual GDP growth rate of 4.5 percent from 2013–2023, and the 2023 observed mean Senegalese income of 840,000 CFA/year (1510 USD/year) (World Bank Group Data, 2025). Agent incomes in the No Aspirations Scenario also exhibit a different income distribution: 49 percent of agents fall under the poverty line (defined at 2.15 USD per day in 2017 purchasing power), compared to 43 percent in the Reference Case (Fig. 3d).[3] Without the ability to form aspirations that incentivize human capital investments, fewer agents accumulate resources required to break out of poverty traps.

4.2. Human capital outcomes

We now turn to our second research question: how do different climate-driven shocks affect agents' migration and education decisions? The environmental change scenarios modeled here – Senegal River Drought and Saltwater Intrusion – lead to aggregate migration rates that mostly overlap with the Reference Case over the duration of the modeled timeframe (Fig. 3a). However, both scenarios provoke temporal shifts in migration rates relative to the Reference Case (Fig. 3b). In particular, the Saltwater Intrusion scenario – affecting traditional migration destinations such as Dakar and Saint Louis – leads to diminished migration rates early in the model timeframe (10–25 percent lower compared to the Reference Case), followed by a spike in migration of up to 10 percent greater than the Reference Case between Years 10–15 and slightly elevated migration for the remainder of the time period (Fig. 3b, purple line). This pattern suggests that the initial effects of saltwater intrusion are to restrict migration into affected regions (see Section 4.3), but ultimately, migration rates recover and even exceed baseline conditions as agents gain information about alternative destinations and livelihoods. By contrast, the time-bound Senegal River Drought hazard – affecting areas that are agriculturally-dependent and traditional regions of out-migration – leads to an approximately 10 percent increase in migration rates after drought onset, followed by a reversion back to baseline rates (Fig. 3b, green line). This reflects the short-term capability of some agents to move in response to diminished incomes in drought-affected areas, but may not reflect fundamental changes in livelihood aspirations among these agents. Further, the fact that migration is initially suppressed by saltwater intrusion, but increases in the drought scenario, suggests that climatic impacts on migration in Senegal may vary substantially depending on the impacted locations and types of shocks, in part mediated by the extent to which such shocks affect livelihood aspirations.

Similarly, while there are no large-scale differences in post-secondary education patterns between the Reference Case, Senegal River Drought, and Saltwater Intrusion scenarios (Fig. 3c), the two climate hazard scenarios change the composition of such investments. Specifically, the Senegal River Drought scenario leads to a slight increase in the number of agents pursuing 2-year vocational training (Fig. 3c, red bar) instead of 4-year university degrees (blue bar), whereas the Saltwater Intrusion scenario leads to a slight increase in the number of agents obtaining *both* 2-year vocational and 4-year university degrees (purple bar). The more prominent role of vocational education in the Senegal River Drought Scenario suggests that relatively low-cost options to increase skills training provide an important livelihood diversification pathway for populations facing time-bound income shocks. By contrast, Saltwater Intrusion results suggest that long-term environmental change prompts affected populations to seek both short-term livelihood diversification pathways and opportunities to pursue longer-term aspirations that are more climate resilient. However, in all cases, agent investing in post-secondary education also work other livelihoods, including agriculture and small businesses, leading to longer timelines for obtaining degrees. On average, it takes an agent 6.7 years to obtain a 4-year university degree and even longer (7.7 years) to obtain a 2-year vocational diploma (Fig. 4), in large part because agents periodically enroll and drop out of classes depending on outside economic opportunities. This resembles patterns

[2] The oscillatory nature of migration rates in Fig. 3a reflects seasonality in migration drivers, as agents from rural areas are more likely to temporarily migrate when crops are growing, and return during the harvesting seasons.

[3] This more closely matches the Senegalese poverty rate measured in the period before our survey data (41 percent in 2011), though the subsequent measure in 2018 reflected a sharp decline to 9.2 percent (World Bank Group Data, 2025).

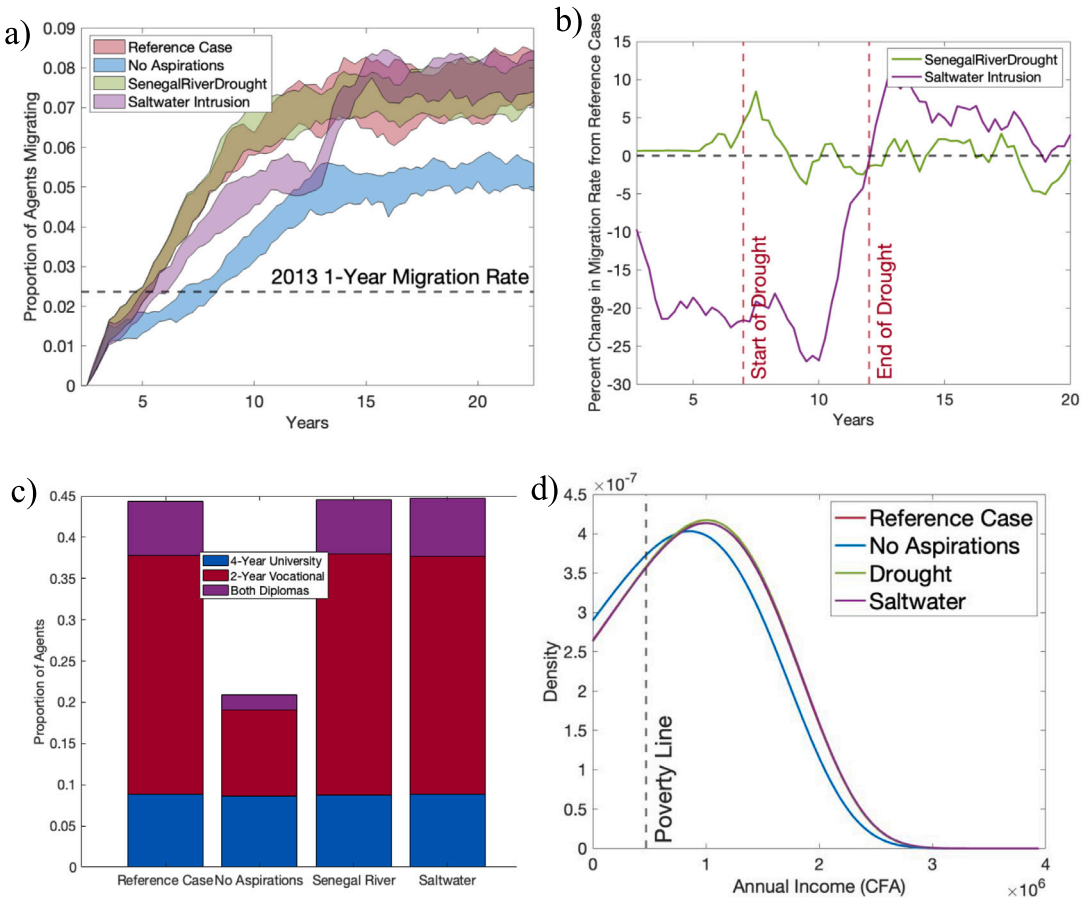

Fig. 3. Comparison of migration and educational outcomes across scenarios. **(a)** Proportion of agents migrating through the model timeframe for the Reference Case (red), No Aspirations (blue), Senegal River Drought (green), and Saltwater Intrusion (purple) scenarios. While all scenarios with aspirations produce similar national migration rates throughout the model timeframe, stabilizing around 6.5–8.5 percent of the population migrating in any year, the No Aspirations Scenario leads to significantly less migration, with only 4.5–5.5 percent of agents migrating in any given year. The horizontal dashed line indicates the 1-year migration rate calculated from the 2013 Senegal National Census. All shaded regions display +/−1 standard deviation of outcomes across 30 simulations with stochastic decisions and social networks. **(b)** Difference in 1-year migration rate between environmental change scenarios and Reference Case. Each line represents the mean difference between the specified environmental change scenario and the Reference Case at the specified time period, expressed as a percent of the Reference Case migration rate. **(c)** The proportion of agents having attained a 4-year post-secondary degree (blue), a 2-year vocational degree (red), or both (purple) across the four modeled scenarios by the end of the modeled simulations (Year 25). Results in panels **b–c** represent average rates across 30 simulations with stochastic agent decisions and social networks. **(d)** Distribution of agent annual incomes by the end of the modeled timeframe for the four scenarios. Each line represents a kernel density plot calculated from the distribution of over 4000 agent incomes across 30 simulations for each scenario. The *x*-axis is expressed in units of 1 million 2018 CFA. The dashed vertical line indicates the annual income equivalent to the World Bank poverty line of 2.15 2024 USD/day. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

observed by our stakeholder group and in policy reports regarding challenges facing the Senegalese post-secondary education system, in which temporary university closures, changing academic cycles, and perceived lack of economic opportunities generally drive ambivalence regarding the value of post-secondary studies (Ambassade de France au Sénégal, 2019; World Bank Group, 2023).

Nevertheless, investments in post-secondary education and/or migration lead to meaningful differences in agents' ability to increase incomes. For example, obtaining a 4-year university degree leads to an increase in mean agent incomes across all scenarios, but to slightly different degrees (Fig. 5a). In the Reference Case (Fig. 5a, red line), obtaining a university diploma increases mean agent incomes from 448,000 CFA/year six years before completion to 756,000 CFA/year by the sixth year after obtaining the diploma, representing a 69 increase. While substantial, the proportional income increase from university education is even higher in the Senegal River Drought (73.1 percent) and Saltwater Intrusion Scenarios (74.6 percent), in which pre-university incomes are substantially lower due to the widespread effects of increased salinity on Senegal's main economic hubs.

By contrast, while 2-year vocational schools offer more limited increases to agent incomes, they can be accessed by a wider range of the population. The pre-enrollment mean income of agents obtaining a 2-year degree is approximately 380,000 CFAs/year across all scenarios — well below the population-wide mean income, and substantially lower than the mean income of those pursuing 4-year university education (Fig. 5d). Further, agents enrolled in vocational schools experience a mean 30–34 percent decrease in income in the six years *prior* to obtaining a diploma, indicating that vocational schools may be particularly sought after by individuals who have recently experienced an income shock. Yet, agents' incomes rise to an average of 657,000 CFAs/year in the six years following graduation from a vocational school. As well, the mean incomes of graduates from vocational school converge to a greater degree between scenarios than do incomes of graduates from 4-year universities, indicating that vocational training (and the livelihoods it enables) may be more resilient to a variety of climate risks. These results assume good alignment between the training provided by post-secondary institutions and the current market needs of higher-income sectors, which has been a challenge in Senegal's

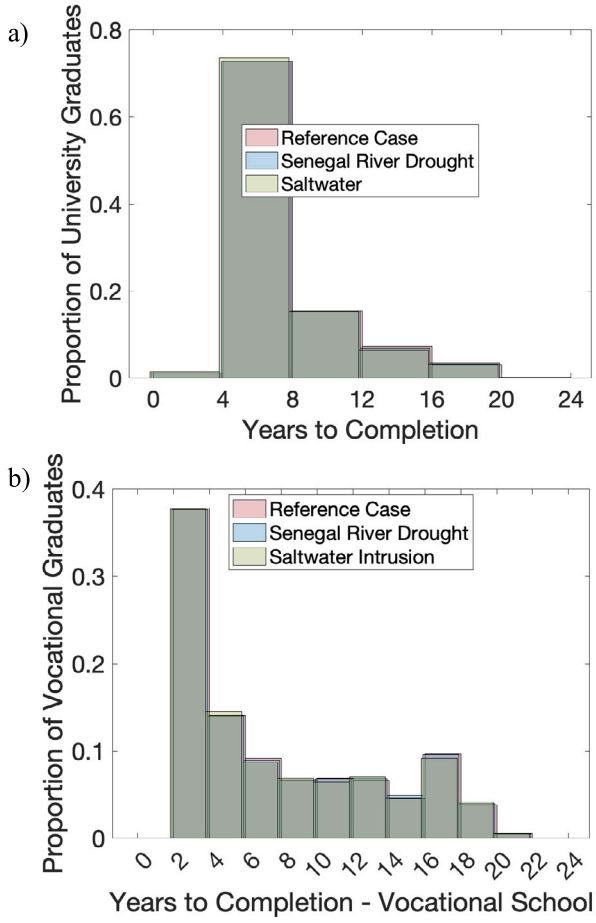

Fig. 4. Distribution of post-secondary degree completion time by scenario. (a) The majority of agents take longer than 4 years to obtain a university degree across all scenarios, with most obtaining a university degree between 4–8 years (overall mean = 6.7 years). **(b)** The distribution of 2-year vocational school graduates indicates that a plurality of agents take between 2–4 years to obtain a vocational diploma, although the mean is much higher (7.7 years), reflecting some agents who only return to vocational schools after an dropping out for an extended period. Note that histogram bars for each scenario are slightly offset for ease of visibility.

emerging vocational schools. We further reflect on this assumption in Section 5.

The return to an individual investment in migration is even starker (Fig. 5c). Across all scenarios, agents who migrate for the first time increase their income from a mean of 89,000 CFA/year in the years prior to migration to 676,000 CFA/year six years after their initial migration trip — a more than 250 percent increase in mean income. Incomes both pre- and post-migration are slightly lower in the Saltwater Intrusion scenario (Fig. 5c, purple line) compared to the other scenarios, again reflecting the impact of this hazard on income-generating sectors along coastal departments. While some of this migration is education-related, this return on migration investment also applies to agents who do not pursue post-secondary education but still move to access better opportunities in the agricultural, service, and small business sectors. Indeed, it is the only form of human capital investment that is accessible to a broad swath of the population, including those with incomes well below the median (Fig. 5d), making it a key part of a pro-poor livelihood strategy (Bell, 2021).

Differences in returns to individual-scale human capital investments – migration, vocational education, and university education – may partially explain why migration remains persistently high in Senegal relative to post-secondary education. Further, our analysis assumes consistent quality of education among university and vocational schools, with diplomas and credentials that are recognized by employers in higher-income sectors. However, this is not necessarily the case in Senegal and across most countries. The quality of post-secondary education can vary widely, leading to substantial variation in the ability of graduates to obtain higher-income employment. With economic opportunities distributed unevenly across the country, and with migrant networks facilitating the ability of agents to locate higher-income opportunities, the relative ease of access and quick returns to migration compared to post-secondary education make this the dominant form of individual human capital investment in the country.

4.3. Population-level outcomes

While long-term, national migration rates do not change substantially between the Reference Case and environmental change scenarios, each environmental shock spurs changes in the geographic distribution of the population. In the Senegal River Drought Scenario, affected departments such as Bakel and Podor initially lose between 2.5–7.5 percent of their population during the drought period relative to the Reference Case Scenario (Fig. 6b, red regions). These regions are particularly affected by the drought owing to their especially high dependence on agricultural livelihoods. Further, some drought-affected regions, such as Bakel, continue to suffer persistent population declines, while others, such as Podor, experience a renewed population influx after the event (Fig. 6f) Importantly, other departments that are not directly affected by the drought also experience long-term population changes. For example, districts near the Senegal River Valley, such as Saint Louis, Ranerou, and Kedougou, experience population increases between 2.5–7.5 percent by the end of the modeled timeframe, indicating that they may serve as nearby "safety zones" to which Senegal River Valley residents move to cope with the drought. Some districts that are farther away, especially along the south-central Atlantic Coast, also experience population increases due to the relative attractiveness of both agricultural and non-agricultural sectors that have not been affected by the drought. These complex migration patterns may reflect a pattern of cumulative causation, in which agents who were among the first to migrate in response to the drought trigger other agents in their networks to also migrate at a later period. At the same time, labor market effects may entice new populations to move into previously drought-affected regions that now have greater labor demand, similar to patterns of in-migration observed after Hurricane Katrina in New Orleans (DeWaard et al., 2016), and simulations of migration responses to sea level rise in Bangladesh (Bell et al., 2021).

Population changes under the Saltwater Intrusion scenario exhibit even more dynamic patterns over the modeled timeframe, reflecting both the chronic nature of this hazard and the importance of this region as a traditional destination for migrants. Initially, a few affected departments along the Atlantic Coast – Tivaoune, Fatick, and Foundiougne – experience declining populations relative to the Reference Case (Fig. 6g). Other departments, including Dakar, Thiès, and Saint Louis, still maintain a robust set of livelihood opportunities, and their populations are not substantially affected by early-onset saltwater intrusion. As effects worsen, some agriculturally-dependent departments (e.g., Fatick) experience more severe population losses, while multiple regions of population increase begin to emerge in the northeast and southwest portions of the country (Fig. 6h). By the end of the modeled timeframe, the population distribution progressively shifts to nearby departments, e.g. Kebemer, Thiès, and Mbour, that are slightly less vulnerable to the effects of saltwater intrusion compared to neighboring departments, as well as departments farther in the interior (e.g. Podor, Kanel, Medina Yorofoula, and Kolda) that have the capacity to absorb labor migrants (Fig. 6i).

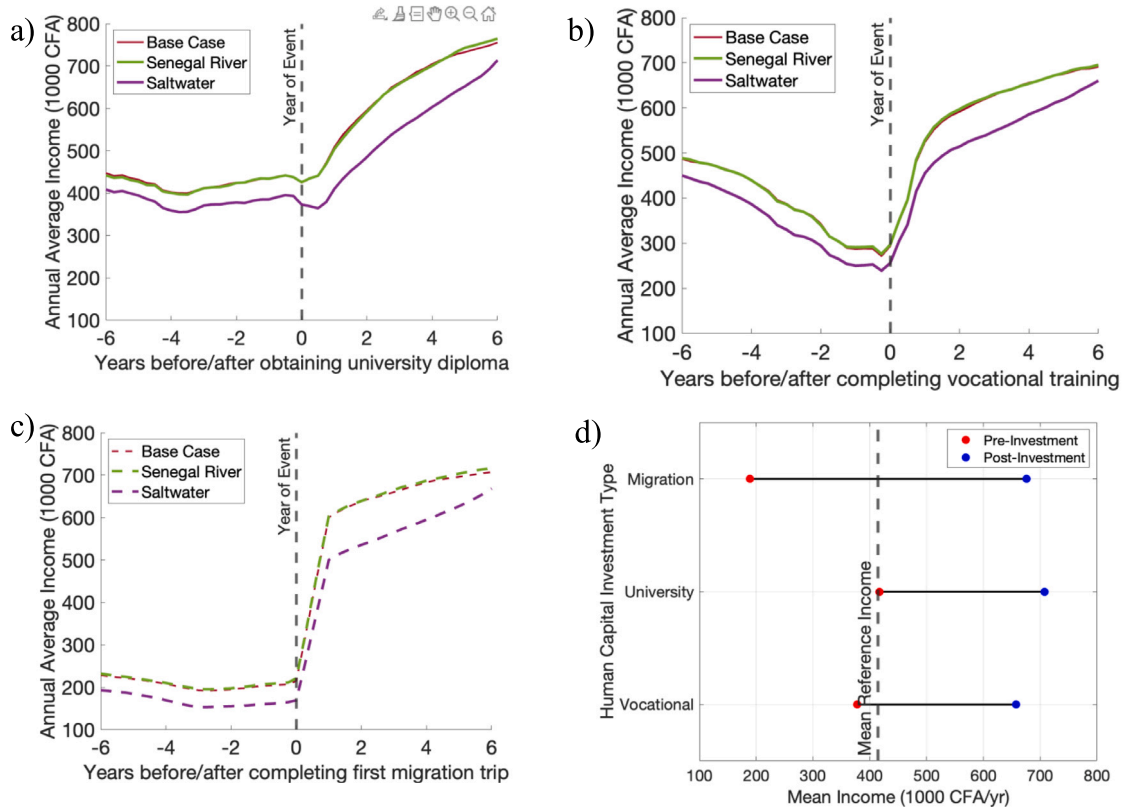

Fig. 5. Comparison of education and migration effects on income. **(a–c)** For agents that completed a 4-year post-secondary degree, 2-year vocational diploma, and a migration trip, respectively, mean incomes are shown for the 6 years prior to and following completion of the specified investment for the Reference Case (red), Senegal River Drought (green), and Saltwater Intrusion (purple) scenarios. The time steps in which each agent earned a diploma and/or engaged in their first migration trip may differ from each other. These plots represent the mean effect of each type of investment on agent incomes throughout the modeled time frame. Note that the lines for the Reference Case and Senegal River Drought scenarios overlap closely in these panels, indicating that the average pre- and post-investment incomes are similar across these two scenarios. **(d)** Comparison of mean agent income in the two years prior (red dots) to investing in migration, university, or vocational education, and the six years following completion of each type of investment (blue dots). Incomes are averaged across all agents in all three scenarios who partake in one of the three specified human capital investments. The dashed vertical line represents the mean income of the agent populations across the entire modeled timeframe for all scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

While changes to population distribution reflect a complex set of factors in each of the environmental change scenarios, a few consistent principles emerge. First, climate-related hazards can exert multi-decadal effects on population distributions — even after regions are no longer directly affected by such hazards, as in the Senegal River Drought scenario. These population shifts are observable implications of several dynamic social processes that are triggered by climate-related shocks — including changing competition in specific labor markets and migrant social networks that transmit new information about destinations to potential migrants. Second, population distributions for a given region may deviate from baseline projections as a consequence of both direct climatic effects that exacerbate migration push factors (i.e., climatic impacts that render a given region less attractive), and indirect effects that attenuate pull factors (e.g., saltwater intrusion decreasing the projected migration flow from interior to coastal Senegal). Especially in places that experience high rates of migration as a baseline condition, indirect effects of climate change may be equally or even greater in magnitude than direct climatic effects. Finally, in resource-constrained countries such as Senegal, much of the climate-induced migration occurs to nearby districts that are still exposed to a particular hazard, but have a greater diversity of livelihood opportunities and are relatively inexpensive to reach for those who have experienced an income shock. Consequently, administrative regions that have not typically been viewed as migrant destinations may quickly emerge as important safety zones for those seeking stable livelihoods, while sometimes simultaneously managing climate shocks themselves. In the Senegal context, our modeling shows that the districts of Podor, Thiès, Nioro du Rop, Sedhiou, and Kolda are particularly likely destinations for climate-induced migrants, given their proximity to several regions exposed to high climatic stress.

5. Discussion

In this study, we develop a new modeling method to represent potential migrants' livelihood aspirations, and their influence on near-term livelihood investments. This framework allows us to endogenize both migration and education decisions in a consistent decision-making framework, which we can use to assess the role of different forms of human capital investments – migration, 2-year vocational training, and 4-year university education – in building resilience to different types of climatic shocks. We integrate this model with quantitative data and qualitative insights from migration and development experts on Senegal, an important case study for investigating how a growing population navigates increasingly severe climate threats in a context with limited public resources. Our analysis points to several theoretical and policy-relevant insights.

Regarding migration theory, we demonstrate the importance of an aspirations framework to modeling heterogeneous responses to climate-linked shocks. First, we illustrate that incorporating agent aspirations in a cohesive decision-making process can lead to a richer set of migration

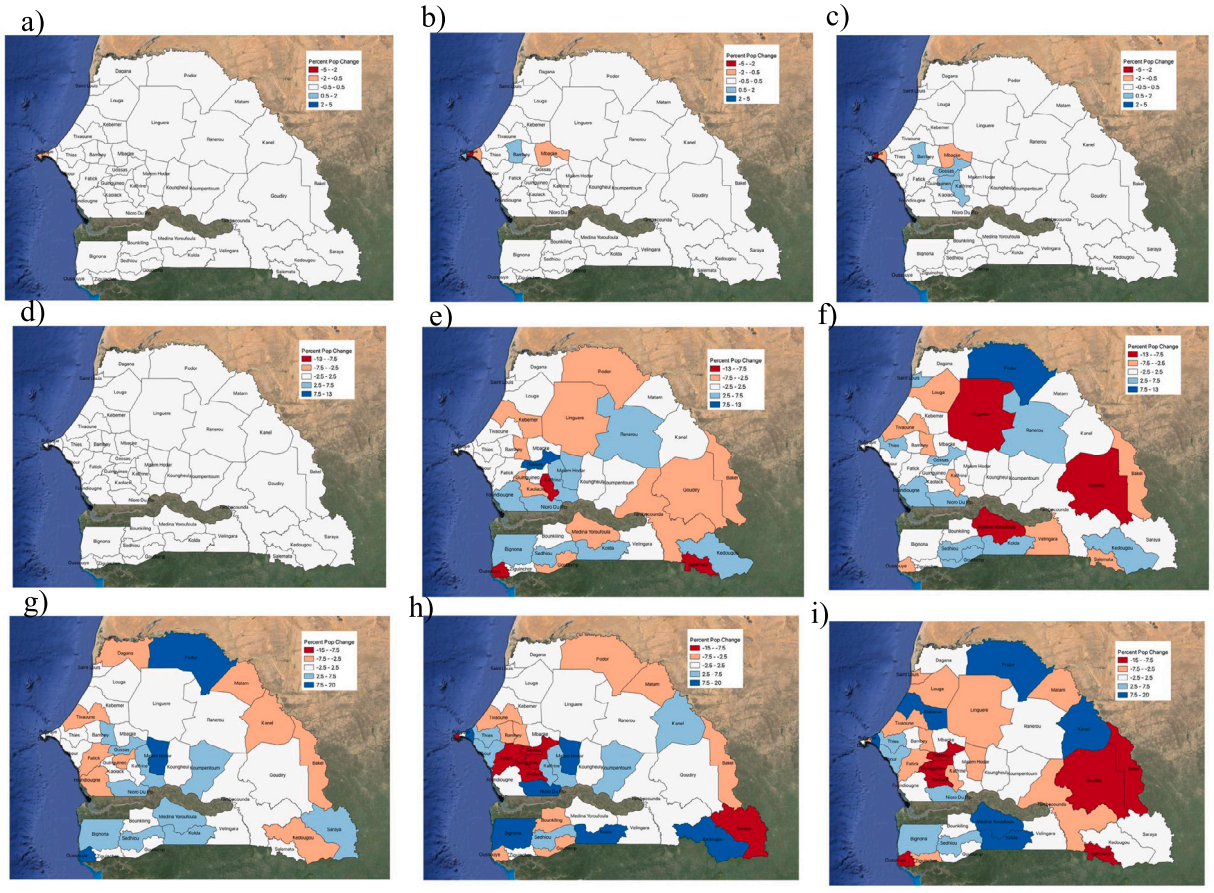

Fig. 6. Population change in Senegal departments for environmental change scenarios, relative to Reference Case. Maps illustrate the proportional change in population for each department at three stages of the model simulation (Years 5–8, Years 12–15, and Years 20–22). **(a–c)** For the Reference Case, the percent change in population for each department is illustrated relative to the population distribution in the model initialization phase (first 10 time steps). Note that the scale in these panels (−5 percent to + 5 percent) is narrower than the other panels, reflecting relatively small baseline population changes. Remaining panels illustrate population changes under the **(d–f)** Senegal River Drought, and **(g–h)** Saltwater Intrusion scenarios. Population changes are calculated relative to the counterfactual Reference Case Scenario. For example, a change of 5 for a department in the Senegal River Drought Scenario indicates a 5 percent increase in population for that department in the stated time window of Senegal River Drought, relative to the same time window of the Reference Case Scenario. Conversely, a change of −5 indicates a 5 percent decline in population for a given department and scenario relative to the Base Case. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and educational decisions (Section 4.1). In our case study, accounting for aspirations increased the proportion of agents that migrate by 45 percent relative to a No Aspirations counterfactual scenario, and increased the proportion of agents pursuing post-secondary education by 110 percent. However, accounting for aspirations also uniformly decreased the female-male ratio of agents pursuing such investments, which matches our stakeholder group's intuition about the relative lack of attractive long-term economic opportunities for Senegalese women, particularly young adults. This approach enables us to account for a wider set of adaptation responses to future environmental shocks.

Second, we demonstrate the crucial role of relatively low-cost and easily accessible forms of human capital investments for building climate resilience. While a 4-year university education remains an inherently beneficial pursuit for many individuals , the ability to migrate and/or access vocational training is especially critical to help individuals escape poverty traps. In our case study, we demonstrate that vocational training and internal migration generate average returns on pre-investment incomes of 43 and 250 percent, respectively. Crucially, these investments are also accessed by agents with lower incomes compared to those pursuing university education, including agents who recently underwent a steep drop in income (in the case of vocational training), highlighting their role as shock-absorbing investments. One caveat to these results is that our analysis assumes consistent quality of education across post-secondary institutions, leading to diplomas and credentials that are recognized by employers in higher-income sectors. In practice, variation in the quality of post-secondary education across institutions – including alignment between courses and market needs, quality of equipment, and the skills of teachers – can drive substantial mismatches between the actual skills of graduates and labor needs of higher-income sectors. Our results should therefore be interpreted as a higher bound on the income returns to post-secondary educational investments.

Third, we demonstrate that while climate-driven shocks may not substantially change overall migration rates, they can exert complex effects on the temporal and spatial redistribution of population within a country. Specifically, regions near climate-vulnerable areas may emerge as nearby safety zones that absorb an influx of migrants who do not have the resources to move to more traditional destinations farther away. This finding echoes recent work in Ethiopia that identifies several forms of "micro-mobilities", or short-distance and short-term movements, that are undertaken by vulnerable populations in response to climatic shocks (Garcia et al., 2025). In the Senegal context, this may engender increasing population movements to an interior set of departments, including Podor, Sedhiou, and Kolda, that have so far been migration *sending* areas, rather than migration destinations (Ministère de l'économie du Plan et de la Coopération, 2024). However,

their proximity to several climate-vulnerable parts of the country and relative capacity to absorb increased labor may spur them to become future destinations. Further, the direct and indirect effects of climate hazards on such population movements persist far beyond the time periods over which regions are exposed to relatively short-term events, including droughts.

These insights provide the basis for specific policy recommendations in building resilience to looming climate threats. First, investments in new vocational schools across different parts of the country, as planned in the *Plan Sénégal Émergent* and the more recent *Vision 2050* development plans, are likely to provide populations in vulnerable regions with accessible, climate-resilient livelihood pathways. Effective policy approaches may also consider pairing the expansion of vocational training opportunities with personal loans for migration and settling into new communities, given the relatively high returns on both forms of human capital investments. Second, the interior crescent of departments could be a high-priority region for further investment in economic development, particularly in the trades and service sectors, given that its population is projected to increase across several climate risk scenarios. This potential change in migration patterns also highlights the importance of complementing national-level human capital investments with local governance mechanisms to secure the necessary land tenure, adequate housing, and access to social services (including education, health, and infrastructure) in receiving areas. This would help mitigate the possibility of new vulnerabilities arising from these population inflows. Third, such investments would ideally be spread over longer time scales, rather than made in short bursts in response to specific climate-related events. Our modeling demonstrates that population responses to a variety of climate hazards are shaped by agents' pre-shock perceptions of attractive livelihood aspirations and continue long after the hazard event, reflecting cumulative causation and other social network effects. Spreading out investments temporally would allow decision-makers at the national and local levels to gradually adjust the geography of livelihood opportunities based on these complex interactions.

In addition to these policy recommendations, we demonstrate the importance of broad stakeholder participation in developing decision-relevant models of climate adaptation. In our experience, including experts from a variety of academic fields (including economics, anthropology, sociology, demography, environmental science, and public policy), professional roles (students, academic researchers, development practitioners), and geographies (West Africa, Europe, and North America) strengthened our ability to identify policy-relevant research questions and structure the model in a way that provides insights for multiple scales and sectors. Specifically, our stakeholder group helped prioritize metrics against which to calibrate our model, identified policy-relevant outputs from our analysis , and informed additions to MIDAS Senegal to reflect important drivers of migration and educational decisions, including the emerging role of vocational schools in shaping livelihood aspirations. This transdisciplinary approach allowed us to investigate complex relationships between migration, education, livelihood, and environmental factors that are often assessed in isolation from each other. Additionally, the participation of migration and development practitioners from Senegal, other West African countries, and Europe provided a more comprehensive perspective on the multiple types and drivers of migration – ranging from local, seasonal mobility as a way of mitigating short-term risks to long-duration migration in pursuit of livelihood aspirations. Nevertheless, we note that our participatory process was not complete: due to limited financial and human resources, it did not engage all relevant societal actors for these questions (e.g., youth groups and direct representatives of rural households). In the future, co-creating research proposals and modeling tools directly with affected communities offers promise for more direct policy impact (Hedelin et al., 2021).

As with any modeling effort, our analysis does not perfectly represent real-world conditions; it is conditioned by several important assumptions and limitations that could be refined in future analyses. One such limitation is our ability to accurately reflect Senegalese sub-populations working in informal economic sectors. We calibrated MIDAS Senegal using statistics on incomes and workforce distribution from the Living Standards Measurement Study and Demographic and Health Surveys, which may struggle to accurately capture informal economic activities that are not explicitly categorized into employment categories (International Labour Organization, 2013). This biases our model towards populations working in more formal occupations, and in particular may not capture how some of the most vulnerable sub-populations respond to climate hazards. Further, while we parameterize MIDAS with relatively high-resolution data at the Administration 2 level (i.e., Senegal's 45 departments), we were constrained by scarce temporal data — essentially, two cross-sectional snapshots of the Senegalese population and economy in 2013 and 2018–19. This limited our ability to track migration on a seasonal basis, including how temporary and circular migration may contribute to climate resilience, particularly to short-term hazards such as floods and heatwaves (Garcia et al., 2025; Lalou and Delaunay, 2017). As well, we are limited in our ability to analyze migration flows *within* these regions, including to secondary urban centers that may increasingly become migration attractors over time. This highlights the value of regular, consistent, and high-frequency data collection to understand fundamental societal responses to evolving climate risks, especially in rapidly-changing regions such as West Africa (Lu et al., 2016; Bell, 2017).

More broadly, while we attempt to model economic livelihood decisions to a relatively high degree of fidelity, MIDAS Senegal does not currently account for more complex motivations for migration and education decisions , including wanderlust, social pressure, and local norms in which embarking on a perilous migration journey forms an integral part of transitioning from adolescence to manhood (Prothmann, 2018). In particular, our stakeholder discussions highlighted the strong norms imposed by the moral economy of rural Senegalese regions, in which livelihood roles and responsibilities are conditioned by a complex web of familial, gender, community, and religious norms (Petit, 2018). Our results should therefore not be interpreted as support for limiting human mobility in return for increasing rural investment - migration has long been intertwined with strong cultural norms and life-meaning in West Africa (Prothmann, 2018; van der Land and Hummel, 2013; Black et al., 2022; Ribot et al., 2020; Romankiewicz and Doevenspeck, 2015). On top of this cultural foundation, we find that migration remains a powerful mechanism for rural populations to improve livelihood outcomes, and is often pursued in tandem with higher education. Yet, nor do our results indicate that migration should be viewed as an adequate climate adaptation strategy on a societal level. Even with relatively high mobility, both fast- and slow-onset climate shocks are likely to substantially reduce incomes and increase poverty (Burzynski and Szymarnska, 2024). From a normative perspective, we wish to emphasize that migration best contributes to human well-being when people have a high degree of agency and legal rights in their migration decisions, and can engage in this process out of a position of high capabilities and livelihood aspirations.

A promising area for future work would be to continue incorporating various aspects of aspirations-capabilities theory into a consistent migration modeling framework. This can include policy levers intended to improve vulnerable populations' agency through either improved capabilities or heightened livelihood aspirations. For example, extending access to low-cost credit could improve near-term capabilities and ease some of the constraints in our model that restricted some agents from accessing human capital investments. Facilitating accurate information about educational and livelihood opportunities throughout the country (e.g., through local radio and TV programs, workshops with community groups, etc.) could also improve agents' abilities to form aspirations that are grounded in real opportunities - motivating more effective individual human capital investments. Beyond education and migration, other societal investments can build human capital,

including improved healthcare infrastructure. Climate shocks have particular ramifications for the health outcomes of mothers and young children (Burrows et al., 2023; Randell et al., 2021; Grace et al., 2015), and correcting for unequal access to quality healthcare in rural spaces can also contribute to enhanced aspirations and capabilities among rural populations. Further, our general approach to endogenizing near-term investments that are motivated by long-term aspirations could incorporate non-pecuniary motivations such as cultural norms (e.g., the desire to fulfill societal norms of masculinity, serving one's community) and place attachment, which have been integrated in models of human behavior in other domains (Bhalla et al., 2024; Castilla-Rho et al., 2017; Tavoni et al., 2012). At an institutional level, factors affecting capabilities, including those affecting both positive and negative liberty, could also be represented, either as exogenous scenarios or through endogenous feedbacks based on how institutions adapt to agents' evolving behavior. As always, a challenge in adding further mechanisms to a model like MIDAS is data availability; without consistent data on non-economic migration factors, calibrating an already complex model to reproduce real-world behavior and interpreting model results becomes increasingly difficult. Still, incorporating such mechanisms based on theory, educated hypotheses, and even limited data can lead to useful sensitivity analyses that identify specific targets for further data collection.

CRediT authorship contribution statement

Nicolas Choquette-Levy: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Fabien Cottier:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Ndèye Coumba Diouf:** Writing – review & editing, Writing – original draft, Validation. **Aboubakr Gambo Boukary:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Véronique Petit:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Etienne Piguet:** Writing – review & editing, Writing – original draft, Validation, Methodology. **Seynabou Sall:** Writing – review & editing, Writing – original draft, Validation. **Corentin Visée:** Writing – review & editing, Writing – original draft, Validation, Methodology. **Alex de Sherbinin:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Andrew Reid Bell:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Anonymized] reports financial support was provided by National Science Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2026.103215.

Data availability

Code used to develop the agent-based model and the Bayesian hierarchical model that provided input data to MIDAS Senegal can be found on the MIDAS GitHub repository at this address: https://github.com/earth-andrew/MIDAS-Senegal.

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