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ORIGINAL PAPER

A framework to link climate change, food security, and migration: unpacking the agricultural pathway

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Abstract
Researchers have long hypothesized linkages between climate change, food security, and migration in low- and middle-income countries (LMICs). One such hypothesis is the "agricultural pathway," which postulates that negative climate change impacts on food production harm livelihoods, which triggers rural out-migration, internally or abroad. Migration is thus an adaptation to cope with the impacts of climate change and bolster livelihoods. Recent evidence suggests that the agriculture pathway is a plausible mechanism to explain climate-related migration. But direct causal connections from climate impacts on food production to livelihood loss to rural out-migration have yet to be fully established. To guide future research on the climate-food-migration nexus, we present a conceptual framework that outlines the components and linkages underpinning the agricultural pathway in LMICs. We build on established environmental-migration conceptual frameworks that have informed empirical research and deepened our understanding of complex human-environmental systems. First, we provide an overview of the conceptual framework and its connection to the agricultural pathway hypothesis in the climate mobility literature. We then outline the primary components and linkages of the conceptual framework as they pertain to LMIC contexts, highlighting current research gaps and challenges relating to the agricultural pathway. Last, we discuss possible future research directions for the climate-food-migration nexus. By highlighting the complex, multiscale, interconnected linkages that underpin the agricultural pathway, our framework unpacks the multiple causal connections that currently lie hidden in the agricultural pathway hypothesis.

Keywords Urbanization · Climate mobility · Climate impacts · Food systems · Food policy · Demography

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Introduction

As climate change continues to harm rural, agriculturally dependent populations in low- and middle-income countries (LMICs), policymakers, researchers, and the public are increasingly keen to understand how climate change may drive rural out-migration (Lustgarten, 2020; Rigaud et al., 2018). But rural out-migration has been happening for centuries – It is driven by a host of factors that extend well beyond climate factors and their impacts on rural communities (Black et al., 2011; Lipton, 1980). Claims of future climate-driven mass migration often ignore the fact that, for any individual or household, the decision to migrate results from complex, multiscale interactions between environmental, social, political, economic, and demographic factors (Black et al., 2011; Boas et al., 2019; Horton et al., 2021). While climate change is clearly impacting rural food production and livelihoods in many LMICs (IPCC, 2022), rural out-migration has historically been explained by the demographic transition and economic theory, which posit that it is primarily driven by attraction to economic opportunities elsewhere (McCarthy & Knox, 2012; Lucas, 2004; Stark & Bloom, 1985). According to foundational development theory (Rostow, 1960), as countries modernize, agricultural production and food security should improve with improved technology and capital, requiring less rural labor demand. The decrease in demand for agricultural workers results in excess rural labor supply and rural residents are thus prompted to migrate to urban settlements, which also attract migrants through jobs in manufacturing and services.

Yet, evidence suggests that the processes and outcomes predicted by development theory have not manifested everywhere. Despite a notable concentration of labor in agriculture, as indicated in Fig. 1A, many low- and middle-income countries (LMICs) continue to rely heavily on food imports, as shown in Fig. 1B, accompanied by persistently high rates of food insecurity (Fig. 1C). Furthermore, rapid urbanization has not always been accompanied by industrialization or urban job creation (Fox, 2012; Henderson et al., 2017; Rodrik, 2016), and the agricultural sector has not mechanized in ways that would reduce demand for rural labor. In Africa, even with rapid urban population growth (UN-DESA, 2018) and the development of the agricultural sector (Jayne et al., 2016, 2022), agricultural labor still comprises nearly 50% of the population (FAO, 2022). Yields for many staples have declined or stagnated over most of the continent (Ray et al., 2012); the region imports 100 million tons of food at a cost of $75 billion per year (African Development Bank Group, 2022) and, by some estimates, Africa imports 85% of its food requirements (Akiwumi, 2020). The rise in food imports is the result of a number of factors, including neo-liberal structural adjustment programs that began in the 1970s, which privileged food imports over local production by reducing agricultural subsidies and extension services to rural producers (Carney & Krause, 2020), as well as neglect of the rural economy, lack of provision of public services to rural communities, and widely held narratives that smallholder food production is of limited value (Brondizio et al., 2023). Today, after decades of decline, food insecurity is now rising precipitously not just in Africa, but in many LMICs worldwide (World Bank, 2023). The reasons driving

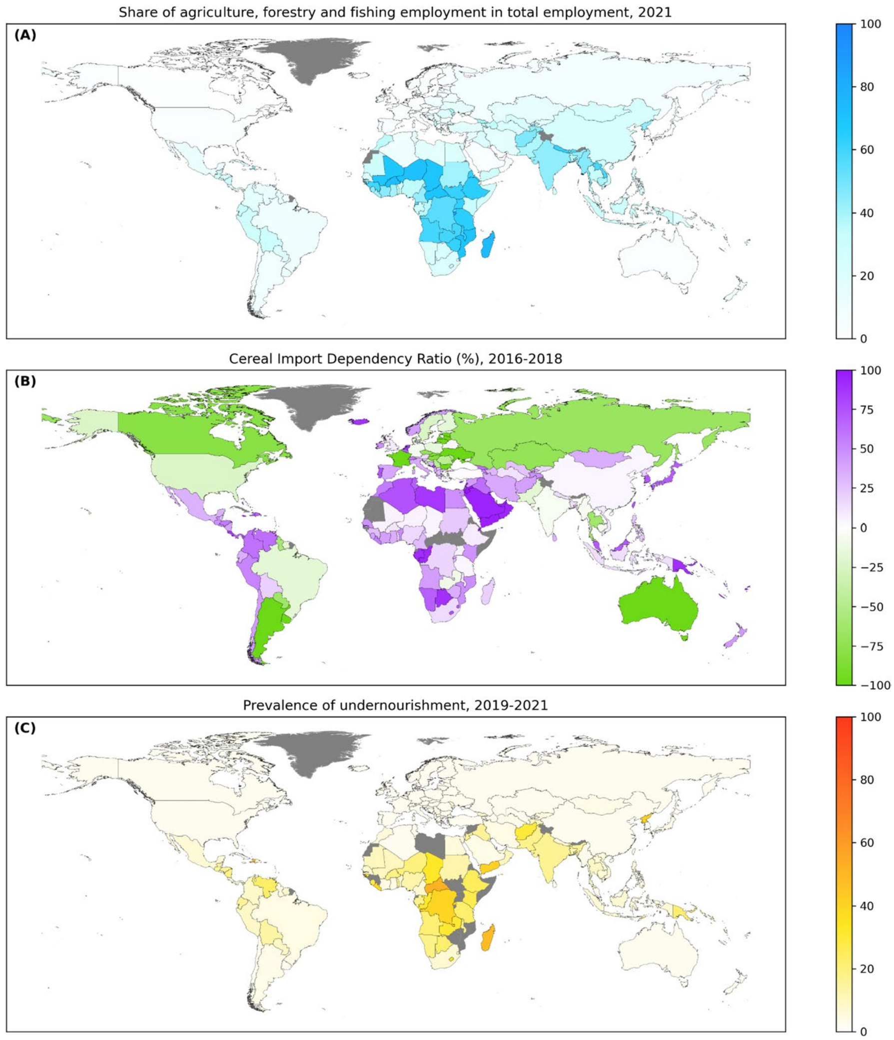

Fig. 1 National-level data for (**A**) the share of total employment in agriculture, forestry, and fishing in 2021; (**B**) average annual cereal import dependency, 2016–2018; and (**C**) average annual prevalence of undernourishment from 2019 to 2021. Data for (A) from (FAO, 2022). Data for (B) and (C) from (FAO, 2023a). Note: gray regions are no data values

the rise in food security are complex, but they can partly be traced to the aforementioned issues, as well as rising prices on international commodity markets, declining imports (e.g., the blockade of Ukrainian wheat), conflicts (Anderson et al., 2021), and – at least in part – climate impacts on food production (Lobell, Bänziger, et al., 2011; Lobell, Schlenker, et al., 2011; Ortiz-Bobea et al., 2021).

Looking ahead, the question is whether increasingly severe climate impacts on food production in LMICs will not only harm rural livelihoods and increase food insecurity but also accelerate rural out-migration to urban and international destinations.

Young people considering whether a future in agriculture is tenable (Brondizio et al., 2023) may look not only at their own experience of climate impacts but also at narratives by the media and development actors that impact are likely to get worse (Ribot et al., 2020; Selby & Daoust, 2021), as they formulate future plans in light of multiple sources of uncertainty (Black et al., 2022). Indeed, a major question is whether rural-to-urban migration in LMICs today is not so much prompted by higher wages and job opportunities in the industrial and service sectors of cities, but rather whether it is triggered by agrarian distress. Furthermore, it is unclear if a rural exodus could trigger further declines in agricultural production, given the degree to which food production is dependent on manual labor in many LMICs.

A common explanation of climate-related migration in LMICs centers on an agricultural pathway (Falco et al., 2019; Hoffmann et al., 2020; Nawrotzki & Bakhtsiyarava, 2017). The agricultural pathway is used as shorthand for hypothesized links between climate change, generally measured by climate anomalies and rural out-migration that is triggered by impacts on the agricultural sector. More specifically, it is hypothesized that negative climate change impacts on food production push rural individuals and households into urban settlements or onwards to international destinations. Migration is thus viewed as an adaptation strategy among smallholders and pastoralists to cope with the impacts of climate change and buttress livelihoods. It is important to note that, for the agricultural pathway to prove valid, it must still account for the social, political, economic, and demographic contexts linked across spatiotemporal scales (Black et al., 2011; Horton et al., 2021). This is because individual and collective agency to adapt to climate and weather extremes is ultimately embedded within socio-political and economic structures (Carr, 2005; Ribot et al., 2020; Turner et al., 2023) and because rural food insecurity ultimately results from entitlement failures (Sen, 1982) – lack of ability to access food due to structural poverty – and not crop failure alone.

While a high proportion of recent studies of climate-related migration in LMICs focus on farmers or farming communities (Zander et al., 2023), and recent reviews and meta-analyses suggest that the agriculture pathway is a plausible mechanism to explain climate-related migration (Hoffmann et al., 2020; Selby & Daoust, 2021), most studies assessing the agricultural pathway fail to establish direct causal linkages between climate impacts, on the one hand, and food production, livelihood loss, food security, and rural out-migration on the other (Falco et al., 2018). Existing agricultural pathway studies tend to indirectly infer climate impacts in relation to migration by assessing the relationship between changes in temperature and precipitation and migration (Müller et al., 2011; Nawrotzki & Bakhtsiyarava, 2017), rather than measuring how climate change directly impacts food production and rural livelihoods, thus accelerating rural out-migration. Few studies employ sufficiently fine-grained data to resolve which rural individuals or households are directly impacted by climate and whether or not such impacts caused individuals or households to migrate (Falco et al., 2019; Hoffmann et al., 2020). Furthermore, research on the agricultural pathway has not yet fully explored how climate change impacts the different pillars of rural food security – namely availability, accessibility, utilization, and stability (FAO, 2008) – nor how potential food insecurity may influence the decision to migrate (Falco et al., 2018). In fact, when migrants are interviewed about their reasons for leaving rural areas, climate change is typically not cited as a reason (Romankiewicz & Doevenspeck, 2015).

Nonetheless, all else being equal, the agricultural pathway offers a useful starting point to explore our current knowledge of how climate change, food security, and migration are linked in LMICs. Climate change continues to impact the nearly 600 million smallholder farmers, who produce at least 30% of the world's food supply on 2 hectares or less (Ricciardi et al., 2018), and the 500 million pastoralists in LMICs (FAO, 2016). Thus, knowing where and why climate change may spur a flight from rural areas and how rural out-migration may impact food security – both directly through changes in agricultural production and indirectly through agricultural labor loss – is imperative if a growing number of LMICs are to avoid increasingly widespread food insecurity.

To guide future research on the climate-food-migration nexus, here, we present a conceptual framework to explicitly outline the components and linkages underpinning the agricultural pathway in LMICs. We build upon previous environmental-migration conceptual frameworks that have been widely adopted for empirical research and have advanced our knowledge of complex human-environmental systems (Black et al., 2011; McLeman et al., 2021). First, we present an overview of a conceptual framework and how it links to the agricultural pathway hypothesis in the climate mobility literature. We then outline the key components and linkages behind the conceptual framework as they apply to LMIC contexts, providing insights into current research gaps and challenges regarding the agricultural pathway. Last, we highlight possible future research directions for the climate-food-migration nexus in LMICs.

A conceptual framework linking climate, food security, and migration

Figure 2 presents our conceptual framework, which elucidates connections from climate change impacts to agricultural production and food security and, via socio-economics, to migration. This framework seeks to unpack individual elements and

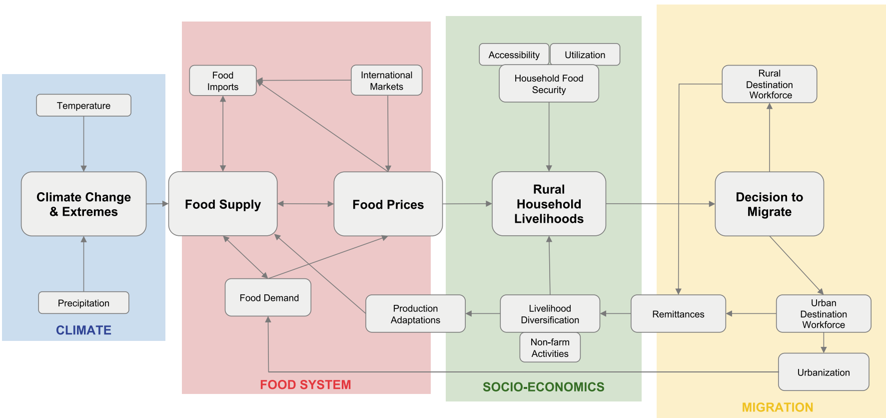

Fig. 2 Conceptual diagram of the components and linkages underpinning the agricultural pathway as a hypothesis to study the climate-food-migration nexus. The diagram is focused on local climate impacts on agriculture and rural households or individuals' decision to migrate. Note that many of these linkages are bidirectional and can be negatively and positively reinforcing

linkages of the agricultural pathway. The presumed, but rarely fully tested linkage (Hoffmann et al., 2020; Falco et al., 2018; Nawrotzki & Bakhtsiyarava, 2017), posits that climate change impacts food security by damaging crops and causing livestock morbidity or mortality, negatively affecting livelihoods, which in turn triggers rural out-migration as either a livelihood diversification or survival strategy, depending on the severity of impacts (Falco et al., 2018). In more extreme cases, degraded livelihoods result in food insecurity because reduced production decreases the availability of food for self-consumption and decreases the accessibility of food by increasing food prices, thereby reducing incomes and labor opportunities and/or making the market for crops and livestock unfavorable.

Yet, most studies citing the agricultural pathway use ecological inference based on the large-area spatial association between migration and environmental factors (Piguet, 2010). In such studies, migration and climate variables are measured over administrative units for a period of time, usually deploying both coarse-grained census data on migration and climate variables that are area-averaged (often population or crop-area weighted), thus making findings susceptible to the ecological fallacy, since results are not based on individual-level data. With a few exceptions (Grace et al., 2018), rarely are direct climate impacts on food production tied to reduced livelihoods and out-migration in a causal inference framework using sufficiently fine-grained climate data tied to food production data and household migration surveys. While we are focused on rural out-migration here, it is important to note that among the poorest rural populations, livelihoods can be so negatively impacted by climate change that they cannot afford to migrate. Thus, the poorest of the poor may be unable to move, which has spurred increasing research interest in so-called trapped or involuntarily immobile populations (Ayeb-Karlsson et al., 2018; Hoffmann et al., 2020; Nawrotzki & Bakhtsiyarava, 2017). This concern is real, but it is outside the scope of this paper, and indeed, the existence of trapped populations is debated (Ayeb-Karlsson et al., 2018).

Climate change impacts result from extreme rapid onset events (e.g., heat waves, droughts, and floods) that can happen individually, serially, or in compound form (two or more events at once) and from long-term climatic shifts that cause slow-onset events like land degradation (Hermans & McLeman, 2021), sea-level rise (Hauer et al., 2019), and soil salinization (Duijndam et al., 2022). The rapid onset events are often superimposed on long-term climate trends that can make them more severe. In the absence of government intervention, international aid, or capital investments, rural individuals and households in LMICs will deploy adaptations such as changing farm practices, rationing food, borrowing capital, sale of household assets, or changing food consumption patterns ("Adaptations as responses to climate change"). Should adaptations not be sufficient, individuals or households will migrate from rural areas, either to urban areas internally or abroad. The agricultural pathway is underpinned by the new economics of labor migration (NELM) theory, which posits that migration is a household risk management strategy, where decisions to send (generally younger male) family members to work in other areas are made at the household level in order to diversify livelihoods and economically support the household unit (de Sherbinin et al., 2022). NELM is invoked both in the case of permanent rural-to-urban migration and seasonal/circular forms of migration between rural and urban areas, though our focus in this paper is more on permanent migration.

Conceptually, the agricultural pathway can be broken into four overarching and interlinked areas: climate, food systems, food security, and migration, as shown in Fig. 2. Each of these areas is underpinned by overlapping components that connect across spatial and temporal scales. Changes to individual components of the pathway can propagate through the climate-food-migration system, resulting in both positive and negative feedback. For example, in a given rural community, if a climate-change-driven drought substantially decreases the harvest and reduces smallholder livelihoods to the extent that households migrate to urban areas, on aggregate such rural out-migration can reduce rural labor supply and, all else equal, decrease future agricultural output which would reduce both rural and urban food security. This hypothetical example is just one of many possible complex feedbacks that need to be resolved to fully test the agricultural pathway hypothesis.

In presenting a conceptual framework to examine the agricultural pathway, we necessarily simplify aspects of this complex socio-ecological system, and we note three caveats. First, governance, institutional arrangements, market dynamics, and the private sector (Daum & Birner, 2017), as well as social and cultural systems (Cundill et al., 2021; Renzaho & Mellor, 2010), mediate many components of the agricultural pathway. But because much of the existing research on the agricultural pathway primarily leverages spatial and economic modeling approaches (Hoffmann et al., 2020) that do not fully account for these factors to inform causal inference (Falco et al., 2018), our conceptual framework does not detail how the components are embedded in context-specific social, cultural, political, and economic systems that influence the decision to migrate (Black et al., 2011; Turner et al., 2023). Second, while there is robust literature on circular and seasonal migration as an adaptation to climate and weather shocks affecting rural populations in LMICs (Thalheimer et al., 2023; Rain, 2018), in presenting our conceptual model, we focus on permanent rural out-migration. By doing so, we aim to simplify the complex dynamics of the framework to more easily inform future research on the potential for large-scale climate-driven migration, a topic about which policymakers and the public are keen to learn more (Lustgarten, 2020; Rigaud et al., 2018). Third, with a few notable exceptions (Zickgraf, 2018, 2022), the agricultural pathway has mostly been examined for terrestrial food producers despite the nearly 500 million people worldwide who are fully or partially dependent on small-scale marine and freshwater fisheries for their livelihoods (FAO, 2023b) and the fact that marine and freshwater food production increasingly face threats from climate change (Tigchelaar et al., 2021).

Empirical evidence for components of the conceptual framework

In this section, we review the evidence from case studies and systematic reviews, reflecting diverse LMIC geographies, in support of the components of our conceptual framework. The literature provides strong evidence that climate change is reducing agricultural production and impacting rural livelihoods in LMICs. We find more modest evidence linking climate change with rural livelihood loss and food security, as well as the connection between food security and migration. We conclude by discussing components of the conceptual framework concerning migration data, patterns, remittances, and evidence regarding rural out-migration and food production.

Climate impacts on agriculture

Impacts of climate on agricultural yields

Globally, climate change has already reduced agricultural productivity by 21% since 1961, and climate change has driven production reductions above 30% in many African, Latin America, and Caribbean countries (Ortiz-Bobea et al., 2021). But the mechanisms by which climate change can affect crops are varied and diverse. For instance, on longer timescales, maize and wheat will experience higher net productivity losses due to temperature increases compared to rice and soybean (Jägermeyr et al., 2021), although losses for wheat are likely to be offset by increases in atmospheric CO_2 concentration (Jägermeyr et al., 2021; Lobell, Bänziger, et al., 2011; Lobell, Schlenker, et al., 2011; Ray et al., 2019; Zhao et al., 2017). The magnitude of the effect that climate change, both negative and positive, has on crop yields increases with higher emissions trajectories (Ray et al., 2019). On interannual timescales, climate variability accounts for roughly one-third of crop yield variability globally (Ray et al., 2015), with extreme climate events affecting both yields and harvested areas of global crops (Lesk et al., 2016). Climate change can also drive increases in rapid onset events that impact food production, including disasters such as floods (Kim et al., 2023), excess moisture (Zampieri et al., 2017), droughts (Kim, Iizumi et al., 2019; Kim, Stites et al., 2019), heatwaves (Lobell, Bänziger, et al., 2011; Lobell, Schlenker, et al., 2011), and combinations of these factors (Lesk et al., 2022). It is also important to note that climate change affects rangeland and livestock, with expected impacts on livestock from drought and heat (Godde et al., 2020; Mauerman et al., 2023; Thornton et al., 2009). Climate change is expected to negatively affect the availability of biomass over the majority of global rangeland areas and increase the heat stress and disease burden to which animals are exposed, thus increasing animal mortality (Godde et al., 2020; Thornton et al., 2009). Climate change will furthermore increase the interannual variability of biomass in most rangelands, which tends to force smallholder pastoralists to permanently offtake animals as herd restocking following a drought takes 3–4 years on average (Godde et al., 2020; Mauerman et al., 2023).

Climate change can reduce food production not only by harming plant and animal physiology but also by reducing agricultural labor productivity (de Lima et al., 2021; Parsons et al., 2021; Tigchelaar et al., 2021; Zander et al., 2023). It is well established that heat extremes pose unsafe working conditions and lower productivity for physically demanding outdoor labor, such as most agricultural labor (de Lima et al., 2021). Concerningly, for the tropics, where most smallholders and pastoralists reside (Fig. 1A), recent research suggests that moist–heat extremes may, at times, already exceed the biophysical limits of human survivability, even for acclimated people (Raymond et al., 2020). Impacts on agricultural labor from extreme heat will continue to increase due to climate change. In fact, future impacts on agricultural production from climate change may be equal to labor loss and crop damage, with production loss due to labor impacts being most accurate in sub-Saharan African and South-East Asia (de Lima et al., 2021).

Given the complex linkages between climate change and food production, clearly specifying the spatiotemporal scale of the climate change component is pivotal to investigating the agricultural pathway. To fully resolve the specific impact climate change has on a given food production system, research on the agricultural pathway needs to clearly state if impacts result from long-term (decadal) climate shifts, interannual variability, increased rapid onset events, or a combination of these changes. After determining the temporal scale of signals from either climate change or climate variability, studies on climate-food-migration should specify which crop or animal production systems are affected and whether the reduction might be attributed to lost labor.

Climate impacts on agricultural markets

In examining the agricultural pathway, the literature has yet to fully account for how climate change affects interactions between agricultural productivity and the sensitivity of prices, consumption, and import and export trends, and how rural producers react to these interactions. A handful of studies that model food production under climate change scenarios assess the relationship between climate change and farmers' adaptation strategies (Guido et al., 2020; Shisanya & Mafongoya, 2016), technological changes (Alhassan, 2020; Savari & Zhoolideh, 2021), market responses (Alvi et al., 2021; Islam et al., 2016; Xie et al., 2020), dietary changes (Alvi et al., 2021), the health of agricultural laborers (de Lima et al., 2021), and population changes (Dawson et al., 2016; Defrance et al., 2020). Importantly, evidence suggests that integrating improved technology and farmers' adaptation practices can offset the negative effects of climate change slightly because technological improvements can aid in increasing or maintaining crop yields, decreasing crop prices, and increasing consumption (Islam et al., 2016). Globally, food self-sufficiency and projected food production are sensitive to changes in diet (Beltran-Peña et al., 2020). Consumer demand and changing preferences in one country can also drive changes in supply from distal countries. For example, increased demand for pork in China has driven the expansion of soy crops in Brazil (Peine, 2013). Additionally, demographic change itself influences the climate-food-migration nexus – models that integrate different future population growth projections find an exacerbation of adverse effects of climate change on food security (Dawson et al., 2016; Defrance et al., 2020). Evidence from West Africa suggests that continued rapid population growth will have a greater effect on food availability compared to decreased yields under climate change projections (Defrance et al., 2020).

Estimating climate impacts on agricultural productivity requires integrating market responses and government actions, such as trade policies, as input variables. By integrating these variables, modelers project a reduction in the magnitude of adverse climate impacts on agricultural productivity (Alvi et al., 2021; Islam et al., 2016; Xie et al., 2020). For example, in response to decreases in crop yields, farmers may refine production practices (e.g., shift the crop calendar) and farm management to limit future crop losses. This can result in more moderate price changes in the future, reduced food imports, and increased food exports, alleviating the negative impacts on food accessibility and consumption (Alvi et al., 2021; Islam et al., 2016; Xie et al., 2020). Government actions, such as providing farmers with subsidies to motivate improved farm management, can result in lower prices for consumers, improvements in exports, and improvements in the food supply available to consumers. However, these subsidies may not be enough to completely offset negative climate effects (Alvi et al., 2021).

Paradoxically, when global price shocks have occurred, rural households in LMICs have reported increased food security compared to urban households. This was the case during the 2007/8 price shock for many African producers who reported increased food security compared to urban households (Verpoorten et al., 2013), suggesting that acute increases in global prices for some commodities may translate into improved incomes and food security for producers. However, food price subsidies in many LMICs evince an urban bias (Bezemer & Headey, 2008), which is driven by a desire to keep prices stable for urban constituencies that are perceived as being more critical to electoral support or the stability of authoritarian regimes, depending on the form of government. This undercuts potential benefits to rural producers from climate-related food price increases.

Socioeconomics

Climate impacts on rural livelihoods

The primary proposed mechanism for the ways in which climate change impacts lead to rural out-migration is through harm to livelihoods. This is supported by a large body of literature focused on how both slow and rapid onset climate change events negatively affect rural livelihoods. For instance, drought-related crop losses are associated with household income declines (Hermans & Garbe, 2019; Sam et al., 2019; Udmale et al., 2015), increased unemployment rates (Sam et al., 2019), heightened livelihood vulnerability (Keshavarz et al., 2017; Thao et al., 2019) and assets vulnerability (Khayyati & Aazami, 2016), elevated poverty levels (Hermans & Garbe, 2019), and increased loan requests (Udmale et al., 2015). In contrast, households with stable financial capital and higher incomes experience less livelihood sensitivity to drought (Keshavarz et al., 2017; Zhu et al., 2020). Furthermore, differences in wealth and how it contributes to differences in the severity of drought impacts are evident in on-farm practices available to households that can offset the adverse effects. This is exemplified by evidence from the 2012 drought in Western India (Udmale et al., 2015): Higher-income households had higher accessibility to irrigation systems, resulting in minimal crop production failure.

Education is fundamental to rural livelihoods, and numerous studies have shown that rural households with higher educational levels are less affected by climate impacts on agriculture. In Kenya, farmers with higher education are more likely to use climate adaptation strategies such as planting drought-tolerant crops, diversifying crops, or growing early maturing crops, as well as diversifying income (Gebre et al., 2023). Similarly, in rural mountain communities of Nepal, households with better education and financial assets have more options to diversify their income to contend with climate change impacts on agriculture (Gentle & Maraseni, 2012). Case studies from other countries such as Pakistan (Khan et al., 2020), Vietnam (Huong et al., 2019), and Ethiopia (Sertse et al., 2021) confirm that higher education levels reduce the impacts of climate events on agricultural livelihoods. These case studies illustrate the potential for education to reduce the impacts of climate change on rural livelihoods and, potentially, modulate rural out-migration.

Adaptations as responses to climate change

Household adaptive capabilities, which are fundamentally related to poverty levels (Wiederkehr et al., 2018), mediate the agricultural pathway as a mechanism to spur migration. Along with migration ("Migration"), adaptations include diversifying income, improving on-farm management, and improving financial management (Keshavarz et al., 2017). Common on-farm adaptation practices to reduce the impact of drought include switching to drought-resistant crop varieties (Shisanya & Mafongoya, 2016), changing sowing times (Shisanya & Mafongoya, 2016), improving irrigation systems (Savari & Zhoolideh, 2021; Shisanya & Mafongoya, 2016), incorporating new technologies such as those that connect farmers to input-sellers (Alhassan, 2020; Savari & Zhoolideh, 2021), and planting new crops (Shisanya & Mafongoya, 2016). Diversifying livelihoods tends to be the chief off-farm adaptation practice, which reduces household dependency on crop production as the primary source of income (Alhassan, 2020; Shisanya & Mafongoya, 2016; Smith & Frankenberger, 2018; Tankari, 2020). Diversifying income practices include wage labor and selling of non-agricultural goods (Hermans & Garbe, 2019; Keshavarz et al., 2017; Zhu et al., 2020). Rural households also use adaptation practices and coping strategies to counteract the negative impacts of floods on livelihoods. Like drought, common adaptation practices preferred by small-scale rural farmers impacted by floods include livelihood diversification, crop diversification, planting crops at different times, using organic manure for fertilizer, and harvesting water for irrigation (Alhassan, 2020). Households that engage in multiple adaptation practices are also less vulnerable to flood shocks (Alhassan, 2020).

It is important to note several challenges when assessing adaptations in the context of the agricultural pathway. First, farmers' perceptions of climate shocks and weather changes can influence the adaptation strategy chosen by a farmer (Guido et al., 2020). Second, for planned adaptation efforts, most lack a consistent commitment to coordination and implementation. This underscores a trend of slow change in adaptation actions taken by communities, including at the local and national government levels (Leal Filho et al., 2022). Finally, despite households having local awareness of the potential impacts of climate change on agro-pastoral livelihoods, factors like a lack of information, credit, finance, and water access may disrupt their ability to adapt adequately (Wiederkehr et al., 2018). But such information may be challenging to capture when assessing the agricultural pathway.

Household food security

The impact of climate change on food production can be so severe that food insecurity itself can be a causal mechanism that drives rural out-migration (Rain, 2018). While much of the research on the agricultural pathway has not fully accounted for the four pillars of individual or household food security (Falco et al., 2018) – which include availability (production), accessibility (ability to afford food or access markets), utilization (nutritional uptake), and stability of the other three pillars over time (FAO, 2008) – for most households, their livelihoods ultimately dictate food security. Even for subsistence farmers and pastoralists, food insecurity resulting from lost production ultimately results from structural poverty (Sen, 1982). In the context of the agricultural pathway, direct impacts from climate change to production create instability, which propagates into the other three pillars.

There is evidence that migration can result from food insecurity (Carney, 2017). But how food security is impacted by climate events is scale-dependent. This is exemplified by recent research on the relationship between flood and food security in sub-Saharan Africa (Reed et al., 2022). Results suggest that floods degrade food security in locations directly affected by flooding by destroying crops, killing livestock, decreasing household income, increasing disease transmission, and limiting access to markets. But flood conditions were also associated with abundant rainfall in adjacent non-flooded areas, which improved crop growth and increased production at the national scale. The findings highlight the complex – and sometimes competing – pathways by which flooding affects food security.

Studies also show that periods of income loss can coincide with periods of food shortages and subsequently with increases in food insecurity levels (Hermans & Garbe, 2019; Sam et al., 2019; Thao et al., 2019), confirming the bidirectionality of the components of the agricultural pathway. Climate impacts on food production propagate into farmers' and pastoralists' ability to access food through purchases. For instance, in Marsabit, Kenya, droughts reduce household income from livestock and require increased expenditure on water. Herd sizes (and therefore household wealth) take an average of 3–4 years to recover (Mauerman et al., 2023). But households that employ on- and off-farm adaptations have lower rates of food insecurity ("Adaptations as responses to climate change"). For drought, adaptation capabilities and livelihood strategies can counteract the negative effects of drought on food security (Hermans & Garbe, 2019; Sam et al., 2019; Thao et al., 2019).

Migration

In this section, we address the final part of our conceptual diagram, which relates to migration. We begin with a consideration of the data types and scales of analysis employed by most studies that identify climate impacts on agriculture (the "agricultural pathway") as the most likely mechanism influencing migration outcomes since these ultimately constrain the inferences that can be made about causal connections. We then address different migration patterns, consider the influence of remittances on food security, and address the impact of migration on food production.

Migration data collection and analysis

While data measurement issues exist for climate observations (Zaitchik & Tuholske, 2021; Verdin et al., 2020; Funk et al., 2015) and projections (Ayugi et al., 2021; Faye & Akinsanola, 2022), components of the food system (e.g., Estes et al., 2022) and food security (Jones et al., 2013; Tuholske et al., 2020), and socioeconomics (Vollmer & Alkire, 2022; Morris et al., 2000), migration is the key outcome of our conceptual framework. As such, here, we review migration measurement to highlight a fundamental challenge of studies that investigate the agricultural pathway: determining where and when rural out-migration has occurred.

The type of migration data used in agricultural pathway research dictates the type of methodology employed. When framed within the broader environmental-migration context, data and analysis for the migration component of the pathway fits into six broad typologies (Piguet, 2010). Type 1 – ecological inference through spatial analysis – has traditionally relied on national-level data but increasingly employs dyadic spatial data that captures flows of migrants between two or more geographies. The assumption with type 1 analysis is that there is a causal relationship between climate change impacts within a geographic area and the flows of people away from it. Aggregate migration flows between two areas can illuminate associations between climate change impacts on food production, livelihood loss, and rural out-migration (Hoffmann et al., 2020). But these aggregate studies do not directly measure how an impact of climate change maps to a specific household's production loss, much less elucidate the ways in which household or community-level adaptation reduces impacts. Thus, as stated above, these studies may be subject to the ecological fallacy that the geographical co-occurrence of two phenomena, as measured, say, at the scale of districts or provinces, means one necessarily caused the other. Hence, we cannot infer that changes or anomalies in temperature or precipitation necessarily resulted in agricultural production losses (and possibly food insecurity) that engendered migration because we do not have the individual or household level data at a fine enough scale to tie these processes together.

Types 2 and 3 map climate change signals to panel survey data that tracks a group of people through time, on the one hand, or a multilevel model, on the other hand, to identify relationships between climate change, production loss, and rural out-migration. Types 2 and 3 tend to be based on case studies since data requirements are high. This means results cannot easily be generalized. Types 4 and 5 focus on historical analogies, like the Dust Bowl in the USA during the 1930s and post-disaster descriptive assessments, respectively. Type 6 studies are qualitative, such as anthropological approaches, and hold promise for elucidating the elements of the agricultural pathway at very local levels, but like types 2 and 3, the results are not easily generalized.

When questionnaires are employed among individual migrants or migrant-sending households, questions generally focus on how perceived temperature and precipitation changes have affected food production and livelihoods, especially in regions where rainfed agriculture is the main source of income. Perceptions of rainfall variations have a stronger relationship with the motivation to migrate compared to perceptions of temperature variation in the short term (Helbling & Meierrieks, 2021;

Schraven & Rademacher-Schulz, 2016; Etzold et al., 2016; Milan & Ho, 2014; Warner & Afifi, 2014; Van Der Geest, Nguyen, and Nguyen 2012; Murali & Afifi, 2014). Yet, perceptions have not always been found to be consistent with measures of climate variability or trends when compared to meteorological data or satellite reconstructions (De Longueville et al., 2020). So, if studies are focused on "objective" measures of climate variability and trends, but migrants choose to move based on perceptions, then the attribution of migration (or non-migration) to climate factors and the agricultural pathway may be misplaced.

Migration patterns

Consistent with NELM theory, migration is a household risk management strategy or adaptation when rural livelihoods are impacted by climate change through lost production. The decision to send (generally younger male) family members to work in other areas is made in order to diversify livelihoods and economically support the household unit (de Sherbinin et al., 2022). While the agricultural pathway conceptual framework presented here focuses on permanent rural out-migration, the framework can also be an entry point to understand how the agricultural pathway may act on other types of migration and mobility. Like food security, livelihoods influence the type of migration. This is because socioeconomic status determines the type of migration and duration of stay at the destination. Lower-income households often do not have the means to migrate internationally, or at least not from low- to high-income countries (Rigaud et al., 2018). Domestic, rural-to-urban, and rural-to-rural migration patterns are observed most frequently with lower-income households, principally at a seasonal timescale (Hermans & Garbe, 2019; Nawrotzki et al., 2016). Evidence suggests that low- and middle-income households will attempt to explore other strategies for improving food security before resorting to migration, such as combining agricultural with non-agricultural activities for income generation (Hermans & Garbe, 2019; Nawrotzki et al., 2016). In fact, the most commonly used household adaptation strategies among agriculture households in dryland Africa is not migration but rather agricultural management (Wiederkehr et al., 2018).

When migration is employed, short-term (or seasonal) migration patterns can help to address food gaps that are often associated with dry season deficits and climate shocks and more long-term migration patterns are applied to discover opportunities for higher income and education. Short-term patterns are usually pursued by households lacking diverse livelihood opportunities (Alam et al., 2020; Etzold et al., 2016). Long-term migration, on the other hand, is usually carried out by households with relatively stable and diverse livelihood opportunities (Christiaensen et al., 2013; Etzold et al., 2016; Milan & Ho, 2014; Warner & Afifi, 2014). Households close to urban centers will also attempt income diversification by combining rural with urban activities. When resorting to migration, evidence suggests households prefer to travel within the same province, district, or country (Hermans & Garbe, 2019; Duda et al., 2018; McLeman et al., 2016; Viswanathan & Kavi Kumar, 2015; Murali & Afifi, 2014; Warner & Afifi, 2014; Van Der Geest et al., 2012). In fact, evidence suggests that migrating to smaller towns and cities may be more advantageous as an avenue to exit poverty than remaining in origins or moving to larger cities (Christiaensen et al., 2013).

Seasonality also influences migration patterns, but seasonal effects can be divergent depending on local social and climate contexts, as well as the crops being produced. For instance, in Bangladesh, members of rural rice-producing households prefer to decrease farm activities and search for agricultural labor activities elsewhere directly after the end of the rainy season (Etzold et al., 2016). In Bangladesh, the rainy season—often regarded as the peak period for food insecurity—is characterized by a limited number of agricultural employment opportunities. If individuals migrate during this season, those lacking the knowledge or skills for more industrial-based employment will encounter few alternative agricultural labor opportunities to address their household's food shortages. A similar pattern has been observed in Mali, where the absence of alternative employment in nearby rural areas during times of drought results in declines in migration (Grace et al., 2018). However, in other geographic regions, such as Punjab, Pakistan, rural migrants prefer to search for labor during the peak season of food insecurity, which coincides with the rainy seasons, to participate in non-agricultural income activities (Ahmad & Afzal, 2021). Other studies from Cambodia (Jacobson et al., 2019) and Northwest Ghana (Schraven & Rademacher-Schulz, 2016) indicate a shift in the seasonal migration patterns of low-income households from the dry to the rainy season. These studies report that the shift is a consequence of rural households suffering from higher food insecurity preferring to take a risk by searching for non-agricultural activities rather than staying behind for an unsuccessful harvest. The shift in migration season can result in a decrease in the rural workforce in the source areas, with the household members left behind, including children and elders, having to take up the slack on farm activities (Jacobson et al., 2019; Schraven & Rademacher-Schulz, 2016). This decrease in the rural workforce, combined with the possibility of insufficient remittances sent back by migrants, can leave households in a cycle of debt and food insecurity stemming from poor harvests (Jacobson et al., 2019).

Migration and remittances

Remittances from migrants are viewed as a key element of household risk management strategies and thus a key element of the agricultural pathway. Both livelihoods and food security can be buttressed by remittances, lowering the likelihood of future rural out-migration. In fact, households with migrants tend to have higher incomes than other households (Alam et al., 2020; Etzold et al., 2016; Hasanah et al., 2017; Murali & Afifi, 2014; Obi et al., 2020; Warner & Afifi, 2014). Accordingly, unlike households without migrant members, households receiving remittances are found to have increased food accessibility, increased diet diversity, and increased consumption of more nutritious foods (Hasanah et al., 2017; Obi et al., 2020). Apart from remittances covering food expenses, remittances are also used to invest in agricultural inputs and technology, therefore supporting agricultural productivity (Choithani, 2017; Schraven & Rademacher-Schulz, 2016; Thomas-Hope, 2017).

Migration and food production

Migration can have a negative relationship with local food production if key household members, including young men, migrate, leaving those left behind with a smaller farm labor force and therefore reduced food production. Evidence from South Asia and the Caribbean shows that a reduced farm labor force led households to decide to stop farming in favor of purchasing imported foodstuffs, with land abandonment becoming a more frequent occurrence (Sunam & Adhikari, 2016; Thomas-Hope, 2017; Kim, Iizumi et al., 2019; Kim, Stites et al., 2019). This results in increased dependence on remittances and food imports.

The degree of dependency can vary by location, even in the same region. For example, remittances in St. Vincent are critically important, as a greater portion of the income is used for food purchases rather than farm investments, reducing the country's local food production (Craven & Gartaula, 2015). However, in nearby Jamaica, part of remittances are also invested in farming activities, in which case the country's food production is not as significantly affected (Thomas-Hope, 2017). Nonetheless, negative impacts on local food production by migration can cause a country to be more dependent on food imports, harming food accessibility for poorer households should food prices rise as a result of international commodity price shocks (Puma et al., 2015; Sunam & Adhikari, 2016). For instance, in rural Tanzania, migration can worsen the food security status of households because remittances sent from migrants are not enough to overcome the region's low agricultural productivity due to reduced agricultural labor and capital inputs and low soil fertility (Duda et al., 2018), and in Cambodia, migration led to labor shortages and child welfare obstacles (Jacobson et al., 2019).

Conclusion

By developing a conceptual framework for the agricultural pathway, we aim to guide future research that fully accounts for the complex, multiscale, interconnected linkages across the climate-food-migration nexus in LMICs. In outlining the main components and linkages, we root our conceptual diagram in evidence that suggests that climate impacts on households tend to operate through intermediate variables such as income changes, livelihood vulnerability, and possibly increased food insecurity that come as a result of the climate variability (Duda et al., 2018; Helbling & Meierrieks, 2021; Obi et al., 2020; Romano & Traverso, 2020; Sunam & Adhikari, 2016; Thomas-Hope, 2017) and that the drivers of climate-induced migration remain context-specific (Thalheimer et al., 2021). We highlight that direct climate impacts on rural food production, while remaining important, are generally not the only driver of rural-to-urban migration (Black et al., 2011) because livelihood resilience and diversification are key to household migration decisions (Cundill et al., 2021; Hermans & Garbe, 2019; Milan & Ho, 2014; Warner & Afifi, 2014; Van Der Geest et al., 2012). Social and financial variables are often the primary factors influencing migration, with environmental risks mentioned less frequently as a main motivator, even in regions deemed as climate change hotspots (Cundill et al., 2021; Romankiewicz & Doevenspeck, 2015). For example, rural households who can access education (e.g., Gebre et al., 2023) and implement adaptation strategies (e.g., Shisanya & Mafongoya, 2016) may be able to cope with increasing impacts on agriculture from climate change across LMIC contexts, and thus, such households may be less inclined to migrate. Perceptions of rising inequality between migrant-sending (and remittance receiving) households and those that do not send migrants may also be at play, motivating more people to migrate (Lipton, 1980; Ribot et al., 2020).

By outlining each component of the agricultural pathway, our framework provides future researchers with more clearly defined causal linkages for explorations of the agricultural pathway. We emphasize that local context, as shown by our discussion on seasonal migration, is key and that hypotheses about how climate change may spur rural out-migration need to be carefully tested. Indeed, the degree to which agricultural production may be impacted by an exodus of rural youth due to climate change (or perceptions that future climate impacts will be dire (Ribot et al., 2020)) is somewhat unclear, but the potential for an exodus has already raised alarm bells among those concerned about rural sustainability and food production in LMICs (Brondizio et al., 2023; Deotti & Estruch, 2016). It is important to note, however, that in some regions such as sub-Saharan Africa, rapid population growth and young age structures may result in the replacement of any lost agricultural labor well before any labor constraints on production are encountered (Fox et al., 2016; Lipton, 1980). While there is a growing literature related to climate migration (Piguet, 2022; Šedová et al., 2021; Hoffmann et al., 2020), and there is evidence that food security can affect internal and international migration (e.g., Sadiddin et al., 2019; Smith & Wesselbaum, 2020), there is less direct evidence that climate-induced food insecurity per se induces increased migration rates (Falco et al., 2018). In fact, recent evidence from rural Niger suggests that migrant-sending households are not more food insecure than other households, but simply have more adult men (Turner et al., 2023). Few studies have connected climate data with *in-situ* data on food production, let alone food security status, among migrant-sending households.

Our conceptual framework has limitations. We do not address governance, despite the influence national-level policy has on both internal and international migration (Massey, 2020). Aligning place-based, bottom-up research with top-down spatial analysis is also fundamental to monitoring current and projecting future drivers of migration (Horton et al., 2021). But our framework does not specifically outline how to align such different research paradigms, nor does it solve the problem of limited data on human mobility. Indeed, future research on the climate-food-migration nexus needs to better connect climate impacts on agriculture to livelihood loss and food insecurity that results in rural out-migration. This will necessarily require more intense data compilation, collection, and integration, as well as more in-depth fieldwork (Rademacher-Schulz et al., 2012), especially longitudinal studies, in rural areas exploring the linkages.

We are encouraged by the potential of mobile phone data (Lai et al., 2019) and advancements using earth observations to enhance top-down approaches (e.g., Rogers et al., 2023) to improve future research. Similarly, recent efforts by funding agencies that emphasize traditional, place-based social science research focused on drivers of climate migration are encouraging (e.g., DoD Minerva, 2022; HABITABLE, 2023). Indeed, only through further research can we make generalizations connecting climate-induced rural food production loss and food insecurity to more permanent forms of rural–urban and international migration, with possible feedback to food security, and elucidate the multiple causal connections that currently lie hidden in the agricultural pathway hypothesis.

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Data availability The data to reproduce Fig. 1 is available from https://www.fao.org/faostat/en/.

Declarations

Competing interests The authors declare no competing interests.

References

African Development Bank Group. (2022). *About Dakar 2 Summit*. December 19, 2022. https://www.afdb.org/en/dakar-2-summit-feed-africa-food-sovereignty-and-resilience/about-dakar-2-summit?source=email&utm_campaign=covid19&utm_content=168330&utm_medium=email&utm_source=email_95

Ahmad, D., & Afzal, M. (2021). Flood hazards, human displacement and food insecurity in rural riverine areas of Punjab, Pakistan: Policy implications. *Environmental Science and Pollution Research International, 28*(8), 10125–10139.

Akiwumi, P. (2020). *COVID-19: A threat to food security in Africa*. UNCTAD.https://unctad.org/news/covid-19-threat-food-security-africa

Alam, G. M., Monirul, K. A., Shahbaz Mushtaq, Md., Sarker, N. I., & Hossain, M. (2020). Hazards, food insecurity and human displacement in rural riverine Bangladesh: Implications for policy. *International Journal of Disaster Risk Reduction, 43*(February), 101364.

Alhassan, H. (2020). Farm households' flood adaptation practices, resilience and food security in the upper east region, Ghana. *Heliyon, 6*(6), e04167.

Alvi, S., Roson, R., Sartori, M., & Jamil, F. (2021). An integrated assessment model for food security under climate change for south Asia. *Heliyon, 7*(4), e06707.

Anderson, W., Taylor, C., McDermid, S., Ilboudo-Nébié, E., Seager, R., Schlenker, W., Cottier, F., De Sherbinin, A., Mendeloff, D., & Markey, K. (2021). Violent conflict exacerbated drought-related food insecurity between 2009 and 2019 in sub-Saharan Africa. *Nature Food, 2*(8), 603–615.

Ayeb-Karlsson, S., Smith, C. D., & Kniveton, D. (2018). A discursive review of the textual use of 'trapped' in environmental migration studies: The conceptual birth and troubled teenage years of trapped populations. *Ambio, 47*(5), 557–573.

Ayugi, B., Ngoma, H., Babaousmail, H., Karim, R., Iyakaremye, V., Sian, K. T. L. K., & Ongoma, V. (2021). Evaluation and projection of mean surface temperature using CMIP6 models over East Africa. *Journal of African Earth Sciences, 181*, 104226.

Beltran-Peña, A., Rosa, L., & D'Odorico, P. (2020). Global food self-sufficiency in the 21st century under sustainable intensification of agriculture. *Environmental Research Letters: ERL [web Site], 15*(9), 095004.

Bezemer, D., & Headey, D. (2008). Agriculture, development, and urban bias. *World Development, 36*(8), 1342–1364.

Black, R., Bellagamba, A., Botta, E., Ceesay, E., Cissokho, D., Engeler, M., Lenoël, A., et al. (2022). Migration drivers and migration choice: Interrogating responses to migration and development interventions in West Africa. *Comparative Migration Studies, 10*(1), 10.

Black, R., Bennett, S. R. G., Thomas, S. M., & Beddington, J. R. (2011). Climate change: Migration as adaptation. *Nature, 478*(7370), 447–449.

Boas, I., Farbotko, C., Adams, H., Sterly, H., Bush, S., van der Geest, K., Wiegel, H., et al. (2019). Climate migration myths. *Nature Climate Change, 9*(12), 901–903.

Brondizio, E. S., Giroux, S. A., Valliant, J. C., Blekking, J., Dickinson, S., & Henschel, B. (2023). Millions of jobs in food production are disappearing—A change in mindset would help to keep them. *Nature, 620*(7972), 33–36.

Carney, M. A. (2017). 'Back there we had nothing to eat': The case of transnational food insecurity. *International Migration, 55*(4), 64–77.

Carney, M. A., & Krause, K. C. (2020). Immigration/migration and healthy publics: The threat of food insecurity. *Palgrave Communications, 6*(1), 1–12.

Carr, E. R. (2005). Placing the environment in migration: Environment, economy, and power in Ghana's central region. *Environment & Planning A, 37*(5), 925–946.

Choithani, C. (2017). Understanding the linkages between migration and household food security in India. *Geographical Research, 55*(2), 192–205.

Christiaensen, L., De Weerdt, J., & Todo, Y. (2013). Urbanization and poverty reduction: The role of rural diversification and secondary towns1. *Agricultural Economics, 44*(4–5), 435–447.

Craven, L. K., & Gartaula, H. N. (2015). Conceptualising the migration–food security nexus: Lessons from Nepal and Vanuatu. *The Australian Geographer, 46*(4), 455–471.

Cundill, G., Singh, C., Adger, W. N., Safra, R., de Campos, K., Vincent, M. T., & Maharjan, A. (2021). Toward a climate mobilities research agenda: Intersectionality, immobility, and policy responses. *Global Environmental Change: Human and Policy Dimensions, 69*(July), 102315.

Daum, T., & Birner, R. (2017). The neglected governance challenges of agricultural mechanisation in Africa – Insights from Ghana. *Food Security, 9*(5), 959–979.

Dawson, T. P., Perryman, A. H., & Osborne, T. M. (2016). Modelling impacts of climate change on global food security. *Climatic Change, 134*(3), 429–440.

de Lima, C. Z., Buzan, J. R., Moore, F. C., Uris, L. C., Baldos, M. H., & Hertel, T. W. (2021). Heat stress on agricultural workers exacerbates crop impacts of climate change. *Environmental Research Letters: ERL [web Site], 16*(4), 044020.

De Longueville, F., Ozer, P., Gemenne, F., Henry, S., Mertz, O., & Nielsen, J. Ø. (2020). Comparing climate change perceptions and meteorological data in rural West Africa to improve the understanding of household decisions to migrate. *Climatic Change, 160*, 123–141.

de Sherbinin, A., Grace, K., McDermid, S., van der Geest, K., Puma, M. J. & Bell, A. (2022). Migration theory in climate mobility research. *Frontiers in Climate, 4,* 882343. https://doi.org/10.3389/fclim.2022.882343

Defrance, D., Sultan, B., Castets, M., Famien, A. M., & Baron, C. (2020). Impact of climate change in West Africa on cereal production per capita in 2050. *Sustainability: Science Practice and Policy, 12*(18), 7585.

Deotti, L., & Estruch, E. (2016). *Addressing rural youth migration at its root causes: A conceptual framework*. Food and Agriculture Organization of the United Nations.
DoD Minerva. (2022). *Research priorities: 2022 Minerva topics of interest.* https://minerva.defense.gov/Research/Research-Priorities/
Duda, I., Fasse, A., & Grote, U. (2018). Drivers of rural-urban migration and impact on food security in rural Tanzania. *Food Security, 10*(4), 785–798.
Duijndam, S. J., Botzen, W. J. W., Hagedoorn, L. C., & Aerts, J. C. J. H. (2022). Anticipating sea-level rise and human migration: A review of empirical evidence and avenues for future research. *Wiley Interdisciplinary Reviews. Climate Change, 13*(1), e747.
Estes, L. D., Ye, S., Song, L., Luo, B., Eastman, J. R., Meng, Z., ... & Caylor, K. K. (2022). High resolution, annual maps of field boundaries for smallholder-dominated croplands at national scales. *Frontiers in Artificial Intelligence, 4*, 744863.
Etzold, B., Ahmed, A. U., Hassan, S. R., Neelormi, S., & Afifi, T. (2016). Rainfall variability, hunger, and social inequality, and their relative influences on migration: Evidence from Bangladesh. In R. McLeman, J. Schade, & T. Faist (Eds.), *Environmental Migration and Social Inequality* (pp. 27–41). Springer International Publishing.
FAO. (2008). An introduction to the basic concepts of food security. FAO. http://www.fao.org/docrep/013/al936e/al936e00.pdf
FAO. (2016). *Pastoralists' Complex Tenure Rights Are Key to Community Resilience. 2016*. https://www.fao.org/news/story/en/item/454844/icode/
FAO. (2022). *World food and agriculture – Statistical Yearbook 2022*. Rome. https://doi.org/10.4060/cc2211en.
FAO. (2023a). FAOSTAT. https://www.fao.org/faostat/en/
FAO. (2023b). *International year of artisanal fisheries and aquaculture closes with many concrete results*. FAO. March 31, 2023. https://www.fao.org/newsroom/detail/IYAFA-2022-closes-with-many-concrete-results-310323/en
Falco, C., Donzelli, D., & Olper, A. (2018). Climate change, agriculture and migration: A survey. *Sustainability: Science Practice and Policy, 10*(5), 1405.
Falco, C., Galeotti, M., & Olper, A. (2019). Climate change and migration: Is agriculture the main channel? *Global Environmental Change: Human and Policy Dimensions, 59*, 101995.
Faye, A., & Akinsanola, A. A. (2022). Evaluation of extreme precipitation indices over West Africa in CMIP6 models. *Climate Dynamics, 58*(3–4), 925–939.
Filho, L., Walter, E. T., Franke, J. A., Andrew, S. M., Abubakar, I. R., Azadi, H., Nunn, P. D., et al. (2022). Understanding responses to climate-related water scarcity in Africa. *The Science of the Total Environment, 806*(Pt 1), 150420.
Fox, S. (2012). Urbanization as a global historical process: Theory and evidence from sub-Saharan Africa. *Population and Development Review, 38*(2), 285–310.
Fox, L., Senbet, L. W., & Simbanegavi, W. (2016). Youth employment in sub-Saharan Africa: Challenges, constraints and opportunities. *Journal of African Economies, 25*(suppl_1), i3–i15.
Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., ... & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations—A new environmental record for monitoring extremes. *Scientific Data, 2*(1), 1–21.
Gebre, G. G., Amekawa, Y., & Fikadu, A. A. (2023). Farmers' use of climate change adaptation strategies and their impacts on food security in Kenya. *Climate Risk Management, 40*, 100495.
Gentle, P., & Maraseni, T. N. (2012). Climate change, poverty and livelihoods: Adaptation practices by rural mountain communities in Nepal. *Environmental Science & Policy, 21*, 24–34.
Godde, C. M., Boone, R. B., Ash, A. J., Waha, K., Sloat, L. L., Thornton, P. K., & Herrero, M. (2020). Global rangeland production systems and livelihoods at threat under climate change and variability. *Environmental Research Letters: ERL [web Site], 15*(4), 044021.
Grace, K., Hertrich, V., Singare, D., & Husak, G. (2018). Examining rural Sahelian out-migration in the context of climate change: An analysis of the linkages between rainfall and out-migration in two Malian villages from 1981 to 2009. *World Development, 109*(September), 187–196.
Guido, Z., Zimmer, A., Lopus, S., Hannah, C., Gower, D., Waldman, K., Krell, N., Sheffield, J., Caylor, K., & Evans, T. (2020). Farmer forecasts: Impacts of seasonal rainfall expectations on agricultural decision-making in sub-Saharan Africa. *Climate Risk Management, 30*(January), 100247.
HABITABLE. (2023). *Linking climate change, habitability and social tipping points: Scenarios for climate migration*.https://habitableproject.org.

Hasanah, A., Mendolia, S., & Yerokhin, O. (2017). Labour migration, food expenditure, and household food security in eastern Indonesia. *The Economic Record, 93*(June), 122–143.

Hauer, M. E., Fussell, E., Mueller, V., Burkett, M., Call, M., Abel, K., McLeman, R., & Wrathall, D. (2019). Sea-level rise and human migration. *Nature Reviews Earth & Environment, 1*(1), 28–39.

Helbling, M., & Meierrieks, D. (2021). How climate change leads to emigration: Conditional and long-run effects. *Review of Development Economics, 25*(4), 2323–2349.

Henderson, J. V., Storeygard, A., & Deichmann, U. (2017). Has climate change driven urbanization in Africa? *Journal of Development Economics, 124*(January), 60–82.

Hermans, K., & Garbe, L. (2019). Droughts, livelihoods, and human migration in northern Ethiopia. *Regional Environmental Change, 19*(4), 1101–1111.

Hermans, K., & McLeman, R. (2021). Climate change, drought, land degradation and migration: Exploring the linkages. *Current Opinion in Environmental Sustainability, 50*(June), 236–244.

Hoffmann, R., Dimitrova, A., Muttarak, R., Cuaresma, J. C., & Peisker, J. (2020). A meta-analysis of country-level studies on environmental change and migration. *Nature Climate Change, September.* https://doi.org/10.1038/s41558-020-0898-6

Horton, R. M., de Sherbinin, A., Wrathall, D., & Oppenheimer, M. (2021). Assessing human habitability and migration. *Science, 372*(6548), 1279–1283.

Huong, N. T. L., Bo, Y. S., & Fahad, S. (2019). Economic impact of climate change on agriculture using Ricardian approach: A case of northwest Vietnam. *Journal of the Saudi Society of Agricultural Sciences, 18*(4), 449–457.

IPCC. (2022). *Climate change 2022: Impacts, adaptation, and vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056. https://doi.org/10.1017/9781009325844.

Islam, S., Cenacchi, N., Sulser, T. B., Gbegbelegbe, S., Hareau, G., Kleinwechter, U., Mason-D'Croz, D., et al. (2016). Structural approaches to modeling the impact of climate change and adaptation technologies on crop yields and food security. *Global Food Security, 10*(September), 63–70.

Jacobson, C., Crevello, S., Chea, C., & Jarihani, B. (2019). When is migration a maladaptive response to climate change? *Regional Environmental Change, 19*(1), 101–112.

Jägermeyr, J., Müller, C., Ruane, A. C., Elliott, J., Balkovic, J., Castillo, O., Faye, B., et al. (2021). Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nature Food, 2*(11), 873–885.

Jayne, T. S., Chamberlin, J., Traub, L., Sitko, N., Muyanga, M., Yeboah, F. K., Anseeuw, W., et al. (2016). Africa's changing farm size distribution patterns: The rise of medium-scale farms. *Agricultural Economics, 47*(S1), 197–214.

Jayne, T. S., Wineman, A., Chamberlin, J., Muyanga, M., & Yeboah, F. K. (2022). Changing farm size distributions and agricultural transformation in sub-Saharan Africa. *Annual Review of Resource Economics, 14*(1), 109–130.

Jones, A. D., Ngure, F. M., Pelto, G., & Young, S. L. (2013). What are we assessing when we measure food security? A compendium and review of current metrics. *Advances in Nutrition, 4*(5), 481–505.

Keshavarz, M., Maleksaeidi, H., & Karami, E. (2017). Livelihood vulnerability to drought: A case of rural Iran. *International Journal of Disaster Risk Reduction, 21*(March), 223–230.

Khan, I., Lei, H., Shah, I. A., Ali, I., Khan, I., Muhammad, I., ... & Javed, T. (2020). Farm households' risk perception, attitude and adaptation strategies in dealing with climate change: Promise and perils from rural Pakistan. *Land use policy, 91*, 104395.

Khayyati, M., & Aazami, M. (2016). Drought impact assessment on rural livelihood systems in Iran. *Ecological Indicators, 69*(October), 850–858.

Kim, W., Iizumi, T., Hosokawa, N., Tanoue, M., & Hirabayashi, Y. (2023). Flood impacts on global crop production: Advances and limitations. *Environmental Research Letters: ERL [web Site], 18*(5), 054007.

Kim, W., Iizumi, T., & Nishimori, M. (2019). Global patterns of crop production losses associated with droughts from 1983 to 2009. *Journal of Applied Meteorology and Climatology, 58*(6), 1233–1244.

Kim, J. J., Stites, E., Webb, P., Constas, M. A., & Maxwell, D. (2019). The effects of male out-migration on household food security in rural Nepal. *Food Security, 11*(3), 719–732.

Lai, S., Erbach-Schoenberg, E. Z., Pezzulo, C., Ruktanonchai, N. W., Sorichetta, A., Steele, J., ... & Tatem, A. J. (2019). Exploring the use of mobile phone data for national migration statistics. *Palgrave communications, 5*(1), 1–10.

Lesk, C., Anderson, W., Rigden, A., Coast, O., Jägermeyr, J., McDermid, S., Davis, K. F., & Konar, M. (2022). Compound heat and moisture extreme impacts on global crop yields under climate change. *Nature Reviews Earth & Environment, 3*(12), 872–889.

Lesk, C., Rowhani, P., & Ramankutty, N. (2016). Influence of extreme weather disasters on global crop production. *Nature, 529*(7584), 84–87.

Lipton, M. (1980). Migration from rural areas of poor countries: The impact on rural productivity and income distribution. *World Development, 8*(1), 1–24.

Lobell, D. B., Bänziger, M., Magorokosho, C., & Vivek, B. (2011). Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change, 1*(1), 42–45.

Lobell, D. B., Schlenker, W., & Costa-Roberts, J. (2011). climate trends and global crop production since 1980. *Science, 333*(6042), 616–620.

Lucas, R. E., Jr. (2004). Life earnings and rural-urban migration. *The Journal of Political Economy, 112*(S1), S29–59.

Lustgarten, A. (2020). The great climate migration has begun. *The New York Times*, December 16, 2020. https://www.nytimes.com/interactive/2020/07/23/magazine/climate-migration.html

Massey, D. S. (2020). Immigration policy mismatches and counterproductive outcomes: Unauthorized migration to the US in two eras. *Comparative Migration Studies, 8*(1), 21.

Mauerman, M., Ross, C., Nébié, E. I., Anderson, W., Jensen, N., & Chelanga, P. (2023). The long-term impact of multi-season droughts on livestock holdings and pastoralist decision-making in Marsabit, Kenya. *Journal of Arid Environments, 211*(April), 104928.

McCarthy, L. M., & Knox, P. L. (2012). *Urbanization: An introduction to urban geography*. Pearson Higher Ed.

McLeman, R., Schade, J., & Faist, T. (2016). *Environmental migration and social inequality*. Springer International Publishing.

McLeman, R., Wrathall, D., Gilmore, E., Thornton, P., Adams, H., & Gemenne, F. (2021). Conceptual framing to link climate risk assessments and climate-migration scholarship. *Climatic Change, 165*(1), 24.

Milan, A., & Ho, R. (2014). Livelihood and migration patterns at different altitudes in the central highlands of Peru. *Climate and Development, 6*(1), 69–76.

Morris, S. S., Carletto, C., Hoddinott, J., & Christiaensen, L. J. (2000). Validity of rapid estimates of household wealth and income for health surveys in rural Africa. *Journal of Epidemiology & Community Health, 54*(5), 381–387.

Müller, C., Cramer, W., Hare, W. L., & Lotze-Campen, H. (2011). climate change risks for African agriculture. *Proceedings of the National Academy of Sciences of the United States of America, 108*(11), 4313–4315.

Murali, J., & Afifi, T. (2014). Rainfall variability, food security and human mobility in the Janjgir-Champa district of Chhattisgarh State, India. *Climate and Development, 6*(1), 28–37.

Nawrotzki, R. J., & Bakhtsiyarava, M. (2017). International climate migration: Evidence for the climate inhibitor mechanism and the agricultural pathway. *Population, Space and Place, 23*(4):e2033.

Nawrotzki, R. J., Schlak, A. M., & Kugler, T. A. (2016). Climate, migration, and the local food security context: Introducing terra populus. *Population and Environment, 38*(2), 164–184.

Obi, C., Bartolini, F., & D'Haese, M. (2020). International migration, remittance and food security during food crises: The case study of Nigeria. *Food Security, 12*(1), 207–220.

Ortiz-Bobea, A., Ault, T. R., Carrillo, C. M., Chambers, R. G., & Lobell, D. B. (2021). Anthropogenic climate change has slowed global agricultural productivity growth. *Nature Climate Change, 11*(4), 306–312.

Parsons, L. A., Shindell, D., Tigchelaar, M., Zhang, Y., & Spector, J. T. (2021). Increased labor losses and decreased adaptation potential in a warmer world. *Nature Communications, 12*(1), 7286.

Peine, E. K. (2013). Trading on pork and beans: Agribusiness and the construction of the Brazil-China-soy-pork commodity complex. *The ethics and economics of agrifood competition* (pp. 193–210). Springer, Netherlands.

Piguet, E. (2010). Linking climate change, environmental degradation, and migration: A methodological overview. *Wiley Interdisciplinary Reviews. Climate Change, 1*(4), 517–524.

Piguet, E. (2022). Linking Climate Change, Environmental Degradation, and Migration: An Update after 10 Years. *Wiley Interdisciplinary Reviews: Climate Change, 13*(1). https://doi.org/10.1002/wcc.746

Puma, M. J., Bose, S., Chon, S. Y., & Cook, B. I. (2015). Assessing the evolving fragility of the global food system. *Environmental Research Letters, 10*(2), 024007.
Rademacher-Schulz, C., Afifi, T., Warner, K., Rosenfeld, T., & Milan, A. (2012). Rainfall variability, food security and human mobility. *Intersections, 10*.
Rain, D. (2018). *Eaters of the dry season: Circular labor migration in the West African Sahel*. Routledge.
Ray, D. K., Gerber, J. S., MacDonald, G. K., & West, P. C. (2015). Climate variation explains a third of global crop yield variability. *Nature Communications, 6*(January), 5989.
Ray, D. K., Ramankutty, N., Mueller, N. D., West, P. C., & Foley, J. A. (2012). Recent patterns of crop yield growth and stagnation. *Nature Communications, 3*(1), 1293.
Ray, D. K., West, P. C., Clark, M., Gerber, J. S., Prishchepov, A. V., & Chatterjee, S. (2019). Climate change has likely already affected global food production. *PLoS ONE, 14*(5), e0217148.
Raymond, C., Matthews, T., & Horton, R. M. (2020). The emergence of heat and humidity too severe for human tolerance. *Science Advances, 6*(19), eaaw1838.
Reed, C., Anderson, W., Kruczkiewicz, A., Nakamura, J., Gallo, D., Seager, R., & McDermid, S. S. (2022). The impact of flooding on food security across Africa. *Proceedings of the National Academy of Sciences of the United States of America, 119*(43), e2119399119.
Renzaho, A. M. N., & Mellor, D. (2010). Food security measurement in cultural pluralism: Missing the point or conceptual misunderstanding? *Nutrition, 26*(1), 1–9.
Ribot, J., Faye, P., & Turner, M. D. (2020). Climate of anxiety in the Sahel: Emigration in xenophobic times. *Public Culture, 32*(1), 45–75.
Ricciardi, V., Ramankutty, N., Mehrabi, Z., Jarvis, L., & Chookolingo, B. (2018). How much of the world's food do smallholders produce? *Global Food Security, 17*(June), 64–72.
Rigaud, R. K., de Sherbinin, A., Jones, B., Bergmann, J., Clement, V., Ober, K., Schewe, J., Adamo, S., McCusker, B., Heuser, S., & Midgley, A. (2018). Groundswell: Preparing for internal climate migration. Washington, DC: The World Bank.
Rodrik, D. (2016). Premature Deindustrialization. *Journal of Economic Growth, 21*(1), 1–33.
Rogers, G., Koper, P., Ruktanonchai, C., Ruktanonchai, N., Utazi, E., Woods, D., ... & Sorichetta, A. (2023). Exploring the relationship between temporal fluctuations in satellite nightlight imagery and human mobility across Africa. *Remote Sensing, 15*(17), 4252.
Romankiewicz, C., & Doevenspeck, M. (2015). Climate and mobility in the West African Sahel: Conceptualising the local dimensions of the environment and migration nexus. In *Grounding Global Climate Change: Contributions from the Social and Cultural Sciences*, edited by Heike Greschke and Julia Tischler, 79–100. Dordrecht: Springer Netherlands.
Romano, D., & Traverso, S. (2020). Disentangling the impact of international migration on food and nutrition security of left-behind households: Evidence from Bangladesh. *The European Journal of Development Research, 32*(4), 783–811.
Rostow, W. W. (1960). *The stages of economic growth: A non-communist manifesto*. Cambridge University Press.
Sadiddin, A., Cattaneo, A., Cirillo, M., & Miller, M. (2019). Food insecurity as a determinant of international migration: Evidence from Sub-Saharan Africa. *Food Security, 11*, 515–530.
Sam, A. S., Abbas, A., Padmaja, S. S., Kaechele, H., Kumar, R., & Müller, K. (2019). Linking food security with household's adaptive capacity and drought risk: Implications for sustainable rural development. *Social Indicators Research, 142*(1), 363–385.
Savari, M., & Zhoolideh, M. (2021). The role of climate change adaptation of small-scale farmers on the households food security level in the west of Iran. *Development in Practice, 31*(5), 650–664.
Schraven, B., & Rademacher-Schulz, C. (2016). Shifting rainfalls, shifting livelihoods: Seasonal migration, food security and social inequality in northern Ghana. In R. McLeman, J. Schade, & T. Faist (Eds.), *Environmental Migration and Social Inequality* (pp. 43–56). Springer International Publishing.
Šedová, B., Čizmaziová, L., & Cook, A. (2021). A meta-analysis of climate migration literature. 29. Center for Economic Policy Analysis. https://doi.org/10.25932/publishup-49982
Selby, J., & Daoust, G. (2021). *Rapid evidence assessment on the impacts of climate change on migration patterns*. Foreign, Commonwealth and Development.
Sen, A. (1982). *Poverty and Famines: An Essay on Entitlement and Deprivation*. OUP Oxford.
Sertse, S. F., Khan, N. A., Shah, A. A., Liu, Y., & Naqvi, S. A. A. (2021). Farm households' perceptions and adaptation strategies to climate change risks and their determinants: Evidence from Raya Azebo district, Ethiopia. *International Journal of Disaster Risk Reduction, 60*, 102255.

Shisanya, S., & Mafongoya, P. (2016). Adaptation to climate change and the impacts on household food security among rural farmers in uMzinyathi district of Kwazulu-Natal, South Africa. *Food Security, 8*(3), 597–608.

Smith, L. C., & Frankenberger, T. R. (2018). Does resilience capacity reduce the negative impact of shocks on household food security? Evidence from the 2014 floods in Northern Bangladesh. *World Development, 102*(February), 358–376.

Smith, M. D., & Wesselbaum, D. (2020). COVID-19, food insecurity, and migration. *The Journal of Nutrition, 150*(11), 2855–2858.

Stark, O., & Bloom, D. E. (1985). The new economics of labor migration. *The American Economic Review, 75*(2), 173–178.

Sunam, R., & Adhikari, J. (2016). How Does transnational labour migration shape food security and food sovereignty? Evidence from Nepal. *Anthropological Forum, 26*(3), 248–261.

Tankari, M. R. (2020). Rainfall variability and farm households' food insecurity in Burkina Faso: Non-farm activities as a coping strategy. *Food Security, 12*(3), 567–578.

Thalheimer, L., Gaupp, F., & Webersik, C. (2023). Systemic risk and compound vulnerability impact pathways of food insecurity in Somalia. *Climate Risk Management, 42*, 100570.

Thalheimer, L., Otto, F., & Abele, S. (2021). Deciphering impacts and human responses to a changing climate in east Africa. *Frontiers in Climate, 3*. https://doi.org/10.3389/fclim.2021.692114

Thao, N. T. T., Khoi, D. N., Xuan, T. T., & Tychon, B. (2019). Assessment of livelihood vulnerability to drought: A case study in Dak Nong Province, Vietnam. *International Journal of Disaster Risk Science, 10*(4), 604–615.

Thomas-Hope, E. (2017). Migration, small farming and food security in the Caribbean: Jamaica and St. Vincent and the Grenadines. *International Migration, 55*(4), 35–47.

Thornton, P. K., van de Steeg, J., Notenbaert, A., & Herrero, M. (2009). The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. *Agricultural Systems, 101*(3), 113–127.

Tigchelaar, M., Cheung, W. W. L., Mohammed, E. Y., Phillips, M. J., Payne, H. J., Selig, E. R., Wabnitz, C. C. C., et al. (2021). Compound climate risks threaten aquatic food system benefits. *Nature Food, 2*(9), 673–682.

Tuholske, C., Andam, K., Blekking, J., Evans, T., & Caylor, K. (2020). Comparing measures of urban food security in Accra, Ghana. *Food Security, 12*, 417–431.

Turner, M. D., Sambo, S. A., Ribot, J., & Faye, P. (2023). The causal nexus of trans-saharan migration: A political ecology approach from Niger. *Geoforum; Journal of Physical, Human, and Regional Geosciences, 144*(August), 103792.

Udmale, P. D., Ichikawa, Y., Manandhar, S., Ishidaira, H., Kiem, A. S., Shaowei, N., & Panda, S. N. (2015). How did the 2012 drought affect rural livelihoods in vulnerable areas? Empirical evidence from India. *International Journal of Disaster Risk Reduction, 13*(September), 454–469.

UN-DESA. (2018). World urbanization prospects 2018. 2018. https://esa.un.org/unpd/wup/

Van Der Geest, K., Nguyen, K. V., & Nguyen, T. C. (2012). Internal migration in the Upper Mekong Delta, Viet Nam: What is the role of climate related stressors? *Asia-Pacific Population Journal / United Nations, 29*(2), 25–41.

Verdin, A., Funk, C., Peterson, P., Landsfeld, M., Tuholske, C., & Grace, K. (2020). Development and validation of the CHIRTS-daily quasi-global high-resolution daily temperature data set. *Scientific Data, 7*(1), 303.

Verpoorten, M., Arora, A., Stoop, N., & Swinnen, J. (2013). Self-reported food insecurity in Africa during the food price crisis. *Food Policy, 39*(April), 51–63.

Viswanathan, B., & Kavi Kumar, K. S. (2015). Weather, agriculture and rural migration: Evidence from state and district level migration in India. *Environment and Development Economics, 20*(4), 469–492.

Vollmer, F., & Alkire, S. (2022). Consolidating and improving the assets indicator in the global multidimensional poverty index. *World Development, 158*, 105997.

Warner, K., & Afifi, T. (2014). Where the rain falls: Evidence from 8 countries on how vulnerable households use migration to manage the risk of rainfall variability and food insecurity. *Climate and Development, 6*(1), 1–17.

Wiederkehr, C., Beckmann, M., & Hermans, K. (2018). Environmental change, adaptation strategies and the relevance of migration in sub-Saharan drylands. *Environmental Research Letters: ERL [web Site], 13*(11), 113003.

World Bank. (2023). Prevalence of undernourishment (% of population). https://data.worldbank.org/indicator/SN.ITK.DEFC.ZS

Xie, W., Huang, J., Wang, J., Cui, Qi., Robertson, R., & Chen, K. (2020). Climate change impacts on China's agriculture: The responses from market and trade. *China Economic Review, 62*(August), 101256.

Zaitchik, B. F., & Tuholske, C. (2021). Earth observations of extreme heat events: Leveraging current capabilities to enhance heat research and action. *Environmental Research Letters, 16*(11).

Zampieri, M., Ceglar, A., Dentener, F., & Toreti, A. (2017). Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. *Environmental Research Letters: ERL [web Site], 12*(6), 064008.

Zander, K. K., Baggen, H. S., & Garnett, S. T. (2023). Topic modelling the mobility response to heat and drought. *Climatic Change, 176*(4), 42.

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M., et al. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences of the United States of America, 114*(35), 9326–9331.

Zhu, R., Fang, Y., Neupane, N., Koirala, S., & Zhang, C. (2020). Drought stress and livelihood response based on evidence from the Koshi River Basin in Nepal: Modeling and applications. *Water, 12*(6), 1610.

Zickgraf, C. (2018). The fish migrate and so must we': The relationship between international and internal environmental mobility in a Senegalese fishing community. *Medzinárodné Vzťahy, 16*. https://orbi.uliege.be/handle/2268/243103

Zickgraf, C. (2022). Relational (im) mobilities: A case study of Senegalese coastal fishing populations. *Journal of Ethnic and Migration Studies, 48*(14), 3450–3467. https://doi.org/10.1080/1369183X.2022.2066263

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