Past, present, and future spatial patterns of migration in West Africa

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Summary

Migration in West Africa has a long history and is influenced by the complex interplay of environmental, social, economic, and political factors. Additionally, migration is becoming an increasingly important climate adaptation strategy, particularly in rural areas dependent on subsistence agriculture that face challenges such as land degradation, changing rainfall patterns, and resource scarcity. People migrate mainly within their own country or across borders within West Africa, either from rural areas to urban centers, for example, in search of economic opportunities, or to less populated rural areas where agricultural land is available. Although migration can increase the resilience of affected households through remittances and more diverse income sources, it also introduces new risks, particularly in rapidly growing urban areas with limited infrastructure and job opportunities. The complex interplay of factors influencing migration highlights the necessity of a nuanced, localized analysis to comprehend the reasons and locations of potential migration due to adverse circumstances. Furthermore, mapping migration patterns is important for identifying spatial inequalities, understanding the causes of vulnerability, and supporting targeted, context-specific adaptation and development measures. However, few studies have mapped areas of vulnerability associated with out-migration in West Africa at a spatially explicit, country-wide level over different time periods. Direct mapping of migration in West Africa is difficult because, for many countries, census data on migration is either unavailable or relates to larger administrative levels. Therefore, alternative methods, such as spatial analysis, are needed to identify migration patterns based on relevant, measurable environmental and socio-economic indicators. This dissertation addressed this gap by providing a spatial assessment of how several co-occurring factors influence migration in Burkina Faso, Nigeria, and Ghana in the past, the present, and the future.

The dissertation consists of three interrelated studies that examine the spatial distribution of the most important factors influencing migration in the focus countries. The overall aim was to determine where and why migration occurs under different environmental and socio-economic conditions. In the first study, historical migration routes and patterns in the focus countries were derived from literature and integrated into the push-pull theory to identify regional differences. In the second study, Ghanaian experts evaluated the importance of socio-economic and environmental factors on migration decisions. Based on these evaluations, the current socio-environmental vulnerability in Ghana was analyzed at the local level using a weighted overlay analysis to locate rural areas where out-migration is likely. In order to assess the plausibility of the results, they were compared with current net migration rates. In the third study, regions where migration may occur in the present and the future in response to environmental hazards, socio-economic vulnerability, and increased exposure were analyzed using a risk assessment framework that included population and climate projections. Experts from Ghana and Nigeria weighed current and future factors influencing migration. Interviews with migrants were used to compare actual migration motives with regions classified as potentially unfavorable.

All three studies revealed differentiated spatial migration patterns within the focus countries. For instance, the northern regions of Burkina Faso have long been the main areas of origin for internal migrants. This is primarily due to persistent drought, land degradation, and limited livelihood opportunities. This trend continues to this day, as recent census data shows a high rate of out-migration from these areas. Existing challenges, such as climate change, armed conflicts, and low agricultural productivity, are exacerbating the situation. The regions Centre and Hauts-Bassins, are important destinations for internal migrants as they host major urban centers.

Several northern Nigerian states, including Kano, Katsina, Borno, Yobe, and Sokoto, have been particularly vulnerable due to erratic rainfall and persistent insecurity due to terrorist attacks. These factors often lead to increased competition for land and resources, as well as environmental pressures and urban growth in the destination areas. Although future climate models indicate an increase in precipitation in some northern states, these benefits will likely be offset by higher temperatures, increased evapotranspiration, and ongoing land degradation. Furthermore, security-related events, such as terrorist attacks, are difficult to predict. Overall, these states are socio-economically disadvantaged compared to the rest of the country. This will probably cause many people to continue leaving these regions. Interviews with migrants have shown that migration in Nigeria is primarily driven by socio-economic factors, even in environmentally vulnerable areas. This highlights the complex and subjective influences behind migration decisions.

Both in the past and present, migration in Ghana has followed a north-to-south direction. The Upper East, Upper West, and Northern regions are characterized by low agricultural productivity, land degradation, and socio-economic deprivation. This is confirmed by spatial vulnerability assessments and net migration rates, indicating that these regions continue to have unfavorable socio-economic and environmental conditions and remain areas of out-migration. In northern Ghana, which is characterized by unfavorable environmental conditions, a connection between migration and environmental hazards could be observed, as migrants mention environmental factors as a reason for migration. Future climate projections suggest that traditional destination areas in the central and southern regions may be at increased risk due to climate change, which could affect the adaptive capacity of communities that receive migrants.

In conclusion, the results emphasize that spatial socio-economic and environmental inequalities and personal aspirations and perceptions strongly influence migration in West Africa. Although the personal dimension plays a critical role in migration decisions, it is difficult to measure with spatial data. Therefore, individual factors were only considered to a limited extent. The mixed-methods approach applied in this dissertation demonstrated how spatial analysis and data visualization contribute to mapping vulnerability, assessing migration patterns, and estimating future developments. The applicability of these methods was confirmed by their broad alignment with current migration rates. Overall, the findings provide a more nuanced understanding of past, present, and future spatial migration patterns and can inform targeted measures in climate adaptation and sustainable migration management in West Africa.

Zusammenfassung

Migration in Westafrika hat eine lange Geschichte und wird von komplexen Wechselwirkungen zwischen ökologischen, sozialen, wirtschaftlichen und politischen Faktoren beeinflusst. Darüber hinaus wird Migration zunehmend zu einer wichtigen Klimaanpassungsstrategie, insbesondere in ländlichen Gebieten, die von Subsistenzlandwirtschaft abhängig sind und mit Herausforderungen wie Bodendegradation, veränderten Niederschlagsmustern und Ressourcenknappheit konfrontiert sind. Migrationsbewegungen finden hauptsächlich innerhalb eines Landes oder grenzüberschreitend innerhalb Westafrikas statt. Menschen migrieren dabei entweder aus ländlichen Gebieten in städtische Zentren, beispielsweise auf der Suche nach wirtschaftlichen Möglichkeiten, oder in weniger dicht bevölkerte ländliche Gebiete, in denen landwirtschaftliche Flächen zur Verfügung stehen. Zwar kann Migration die Widerstandsfähigkeit der betroffenen Haushalte durch Geldüberweisungen und diversifizierte Einkommensquellen erhöhen, sie bringt jedoch auch neue Risiken mit sich, insbesondere in schnell wachsenden städtischen Gebieten mit begrenzter Infrastruktur und Beschäftigungsmöglichkeiten. Das komplexe Zusammenspiel der Faktoren, die Migration beeinflussen, unterstreicht die Notwendigkeit einer differenzierten, ortsbezogenen Analyse, um die Gründe und Herkunftsorte potenzieller Migrationsbewegungen aufgrund widriger Umstände zu verstehen. Darüber hinaus ist die Kartierung von Migrationsmustern wichtig, um räumliche Ungleichheiten zu erkennen, die Ursachen der Anfälligkeit nachvollziehen zu können und um gezielte, kontextspezifische Anpassungs- und Entwicklungsmaßnahmen zu ermöglichen. Allerdings haben nur wenige Studien vulnerable Gebiete im Zusammenhang mit Abwanderung in Westafrika auf explizit räumlicher, landesweiter Ebene und über verschiedene Zeiträume hinweg kartiert. Eine direkte Erfassung von Migration in Westafrika ist schwierig, da für viele Länder entweder keine Migrationsdaten aus Einwohnererhebungen verfügbar sind oder sich diese auf größere Verwaltungsebenen beziehen. Daher sind alternative Methoden wie räumliche Analysen erforderlich, um Migrationsmuster auf der Grundlage relevanter, messbarer umweltbezogener und sozioökonomischer Indikatoren zu ermitteln. Die vorliegende Dissertation schließt diese Lücke, indem sie eine räumliche Bewertung dessen vornimmt, wie mehrere gemeinsam auftretende Faktoren Migration in den drei Untersuchungsländern Burkina Faso, Nigeria und Ghana beeinflussen.

Die Dissertation besteht aus drei miteinander verknüpften Studien, die die räumliche Verteilung der wichtigsten Einflussfaktoren für Migration in den Fokusländern untersuchen. Das übergeordnete Ziel bestand darin, festzustellen, wo und warum unter verschiedenen ökologischen und sozioökonomischen Bedingungen Migration stattfindet. In der ersten Studie wurden historische Migrationsrouten und -muster aus der Literatur abgeleitet und in die Push-Pull-Theorie integriert, um regionale Unterschiede zu ermitteln. In der zweiten Studie bewerteten ghanaische Experten die Bedeutung sozioökonomischer und ökologischer Faktoren für Migrationsentscheidungen. Auf der Grundlage dieser Bewertungen wurde die derzeitige sozioökologische Vulnerabilität in Ghana auf lokaler Ebene mittels einer gewichteten Überlagerungsanalyse untersucht, um ländliche Regionen zu ermitteln, aus denen eine Abwanderung wahrscheinlich ist. Um die Plausibilität der Ergebnisse

zu beurteilen, sind diese mit aktuellen Nettomigrationsraten verglichen worden. In der dritten Studie wurden mithilfe eines Risikobewertungsrahmens, in den Bevölkerungs- und Klima-projektionen integriert wurden, jene Regionen identifiziert, aus denen aufgrund von Umweltgefahren, sozioökonomischer Anfälligkeit und erhöhter Exposition in der Gegenwart sowie in der Zukunft Abwanderung stattfinden könnte. Experten aus Ghana und Nigeria bewerteten aktuelle und zukünftige Faktoren, die Migration beeinflussen. Ein Vergleich der tatsächlichen Migrationsmotive mit den als potenziell ungünstig eingestuften Regionen erfolgte mithilfe von Interviews mit Migranten und Migrantinnen.

Alle drei Studien zeigten differenzierte räumliche Migrationsmuster innerhalb der Fokusländer. So sind die nördlichen Regionen Burkina Fasos beispielsweise seit langem die Hauptherkunftsgebiete für Binnenmigranten- und migrantinnen. Dies ist in erster Linie auf anhaltende Dürre, Boden-degradation und begrenzte Möglichkeiten für die Sicherung des Lebensunterhalts zurückzuführen. Diese Entwicklung hält bis heute an, denn aktuelle Angaben der Volkszählung zeigen eine hohe Abwanderungsrate aus diesen Gebieten. Bestehende Herausforderungen wie der Klimawandel, bewaffnete Konflikte und eine geringe landwirtschaftliche Produktivität verschlechtern die Situation zusätzlich. Die Regionen Centre und Hauts-Bassins sind wichtige Zielgebiete für interne Migranten und Migrantinnen, da sich dort bedeutende urbane Zentren befinden.

Mehrere Bundesstaaten im Norden Nigerias, darunter Kano, Katsina, Borno, Yobe und Sokoto, sind aufgrund unregelmäßiger Regenfälle und anhaltender Unsicherheit durch terroristische Anschläge besonders gefährdet. Diese Faktoren führen häufig zu einem verstärkten Wettbewerb um Land und Ressourcen, zu Umweltbelastungen sowie zu städtischem Wachstum in den Zielgebieten der Migranten und Migrantinnen. Zwar deuten künftige Klimamodelle auf eine Zunahme der Niederschläge in einigen nördlichen Staaten hin, doch werden diese Vorteile wahrscheinlich durch höhere Temperaturen, erhöhte Evapotranspiration und fortschreitende Bodendegradation relativiert. Darüber hinaus lassen sich Ereignisse wie Terroranschläge nur schwer vorhersagen. Insgesamt sind diese Staaten im Vergleich zum Rest des Landes sozioökonomisch benachteiligt. Dies wird wahrscheinlich dazu führen, dass viele Menschen diese Gebiete weiterhin verlassen werden. Interviews mit Migranten und Migrantinnen haben gezeigt, dass Migration in Nigeria in erster Linie von sozioökonomischen Faktoren bestimmt wird, selbst in Gebieten, die von Umweltgefahren beeinflusst werden. Dies verdeutlicht die komplexen und subjektiven Einflüsse, die hinter Migrationsentscheidungen stehen.

In Ghana erfolgte Migration in der Vergangenheit wie auch heute meist von Norden nach Süden. Die Regionen Upper East, Upper West und Northern sind durch geringe landwirtschaftliche Produktivität, Bodendegradation sowie sozioökonomische Benachteiligung gekennzeichnet. Dies wird durch Bewertungen der räumlichen Anfälligkeit und durch Nettomigrationsdaten bestätigt, die darauf hinweisen, dass in diesen Regionen weiterhin ungünstige sozioökonomische und ökologische Bedingungen vorherrschen und sie nach wie vor Abwanderungsgebiete sind. Im Norden Ghanas, der durch ungünstige Umweltbedingungen gekennzeichnet ist, konnte ein

Zusammenhang zwischen Migration und Umweltgefahren festgestellt werden, da die Migranten und Migrantinnen Umweltfaktoren als Grund für Migration anführen. Zukünftige Klimaprojektionen deuten darauf hin, dass die traditionellen Zielgebiete in den zentralen und südlichen Regionen durch den Klimawandel stärker gefährdet sein könnten. Dies könnte die Anpassungsfähigkeit der Gemeinden, die Migranten und Migrantinnen aufnehmen, beeinträchtigen.

Die Ergebnisse verdeutlichen, dass räumliche sozioökonomische und ökologische Ungleichheiten sowie persönliche Erwartungen und Wahrnehmungen Migration in Westafrika stark beeinflussen. Die persönliche Dimension ist zwar für Migrationsentscheidungen maßgeblich, doch ist es schwierig, sie mit räumlichen Daten zu erfassen. Deshalb war nur eine begrenzte Berücksichtigung möglich. Räumliche Analysen und Datenvisualisierungen können dazu beitragen, Vulnerabilitäten zu kartieren, Migrationsmuster zu bewerten und zukünftige Entwicklungen abzuschätzen. Dies wurde durch den in dieser Dissertation angewandten Mixed-Methods-Ansatz verdeutlicht. Ihre weitgehende Übereinstimmung mit den aktuellen Migrationsraten bestätigt die Anwendbarkeit dieser Methoden. Insgesamt bieten die Ergebnisse ein differenziertes Verständnis vergangener, gegenwärtiger und zukünftiger räumlicher Migrationsmuster und können als Grundlage für zielgerichtete Maßnahmen zur Klimaanpassung und zum nachhaltigen Migrationsmanagement in Westafrika dienen.

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ACLED	Armed Conflict Location and Event Data project
AR5	IPCC Fifth Assessment Report
AR6	IPCC Sixth Assessment Report
CDD	Consecutive dry days
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CI	Composite indicator
CIESIN	Centre for International Earth Science Information Network
CMIP6	Coupled Model Intercomparison Project Phase 6
DHS	Demographic and Health Surveys Program
ECMWF	European Centre for Medium-Range Weather Forecasts
ECOWAS	Economic Community of West African States
ERA5	ECMWF Reanalysis v5
ESGF	Earth System Grid Federation
FCT	Federal Capital Territory
GDP	Gross domestic product
GHSL	Global Human Settlement Layer
GSS	Ghana Statistical Service
IDP	Internally displaced people
IOM	International Organization for Migration
IPCC	Intergovernmental Panel on Climate Change
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
ITCZ	Inter-Tropical Convergence Zone
KGE	Kling-Gupta efficiency
LGA	Local government area
LULCC	Land use and land cover change
MAE	Mean Absolute Error
MODIS	Moderate-resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
PHC	Population and Housing Census
RCP	Representative Concentration Pathway
RII	Relative Importance Index
SDG	Sustainable Development Goals
SSP	Shared Socioeconomic Pathway
UNDESA	United Nations Department of Economic and Social Affairs
WASCAL	West African Science Service Centre on Climate Change and Adapted Land Use
WOA	Weighted Overlay Analysis

1 Introduction

Migration has long been a part of everyday life in West Africa, influenced by a complex interplay of economic, social, political, and environmental factors (Black et al., 2022; Zachariah and Condé, 1981). In this context, migration refers to the movement of people from one place to another, either within a country or across national borders. Colonialism introduced physical borders and administrative controls that disrupted traditional migration patterns, which led to the formal separation of ethnic groups within the region. Despite these disruptions, migration continued, especially in the form of seasonal labor migration from the savanna regions to coastal areas, where migrants searched for work in mines, the agricultural sector, or urban centers (Clottey and Aqyei, 2007; Teye, 2022). Today, migration has become a key climate adaptation strategy and a response to overlapping environmental, socio-economic, and demographic pressures (Teye and Nikoi, 2022). In many rural areas of West Africa, people are heavily dependent on subsistence agriculture and natural resources (Sultan and Gaetani, 2016). These areas face increasing challenges, including land degradation, changing rainfall patterns, and land scarcity (van der Land et al., 2018). In turn, these conditions can reduce agricultural productivity and have a negative impact on livelihoods (Borderon et al., 2019; IPCC, 2022). Migration in West Africa is often internal and varies depending on the resources and networks available to individuals and households (Teye, 2022). Individuals move to urban centers for income opportunities, education, or access to services (Arthur-Holmes and Abrefa Busia, 2022; Longueville et al., 2019) or relocate to less densely populated rural areas where land for agriculture is still available (van der Geest, 2011). In the future, demand for food, water, and housing is expected to increase, particularly in urban areas, due to in-migration and population growth (Arfasa et al., 2024; Asabere et al., 2020; Kassouri, 2021). Agricultural regions will face growing pressure on land and water resources, and some areas may become less suitable for producing staple crops due to climate change (Akpoti et al., 2022; Egbebiyi et al., 2019). These developments will influence future migration patterns (Rigaud et al., 2021; Trisos et al., 2023).

In many cases, migration is not a direct response to environmental change, but part of a broader strategy to cope with uncertainty, diversify income or adapt to local conditions (Hoffmann et al., 2022). Although the relationship between environmental factors, including climate change, and migration is increasingly discussed in research (Kaczan and Orgill-Meyer, 2020; Koubi et al., 2016), its role remains difficult to isolate (Mukherjee and Fransen, 2024; Osei-Amponsah et al., 2023). The broader question of how different factors interact to influence migration decisions persists, and generalizations are often difficult due to local variability. Despite the growing importance of understanding environmental influences on migration, studies that systematically integrate environmental, socio-economic, and demographic factors remain limited in the West African context. Much of the existing literature is either qualitative (Arthur-Holmes and Abrefa Busia, 2022; Michael, 2024), not spatial-explicit (Bohra-Mishra et al., 2014; Helbling and Meierrieks, 2023), based on small-scale case studies within a single country (e.g. Abu 2022), or narrowly focused on climate factors while giving limited attention to socio-economic conditions (Martínez Flores et al., 2024). This makes it challenging to identify broader patterns or design targeted policy measures.

Spatial patterns of unfavorable factors play a crucial role in shaping who migrates, from where, and under what circumstances. Environmental and socio-economic factors often act as interconnected drivers, affecting migration decisions in various ways based on local conditions (Borderon et al., 2019; Niva et al., 2021). The mapping of vulnerable areas at high spatial resolution can be used to identify patterns of potential out-migration and define policies tailored to local contexts (Birkmann et al., 2021; Hoffmann et al., 2022). The following subchapters discuss the current state of research on environmental and socio-economic challenges and the role of migration in rural West Africa, as well as methods for measuring migration patterns.

1.1 Environmental and socio-economic challenges in West Africa

Climatic conditions in the West African sub-region range from humid tropical forests to arid deserts. Due to their reliance on rain-fed agriculture, communities in West Africa are especially vulnerable to climate-related hazards (Sultan and Gaetani, 2016). Rising temperatures and erratic rainfall patterns have already led to severe droughts and floods, exacerbating existing vulnerabilities (Codjoe and Atiglo, 2020; Miller et al., 2022). Furthermore, coastal areas in countries such as Ghana and Nigeria face severe erosion due to rising sea levels and frequent flooding (Boateng et al., 2017; Ikuemonisan and Ozebo, 2020). These climate-related impacts challenge progress toward the Sustainable Development Goals (SDGs), particularly those linked to food security, health, education, and urban resilience (Codjoe and Atiglo, 2020). In general, climate change is already slowing down efforts to overcome inequality in African countries (Baarsch et al., 2020).

The extent and impacts of future climate change in West Africa vary across climate scenarios and agro-ecological zones (Bobde et al., 2024; Dieng et al., 2022). However, there is widespread agreement that West Africa will experience increasing extreme temperatures and precipitation in the coming years (Fitzpatrick et al., 2020). Heat stress is projected to affect 20-50% of the population in West Africa as global temperatures rise, posing severe health risks (Fotso-Nguemo et al., 2023; Freychet et al., 2022). Rainfall patterns are projected to change, with increased daily rainfall rates and later rainy season onsets (Bobde et al., 2024; Fitzpatrick et al., 2020). Aryee et al. (2024) highlight increased flood risk, especially in the Savanna and Sahel zones. Climate models project yield losses for major cereal crops across most West African countries by mid-century, driven primarily by increased temperatures (Ahmed et al., 2016).

These impacts intersect with pre-existing socio-economic vulnerabilities across the region (Fitzpatrick et al., 2020; Trisos et al., 2023). For example, the Sahel zone is experiencing intensified conflicts due to the adverse effects of climate change. In areas of limited economic opportunity and political exclusion, these resource scarcities can lead to violent conflict (Koubi, 2019). Limited availability of key resources such as water, arable land and pasture is disrupting livelihoods and contributing to conflicts between pastoralists and farmers (Larémont, 2021). Armed conflicts, particularly terrorist violence, disrupt local food systems and agricultural production by reducing farmed land and discouraging investment in inputs such as fertilizers (Béné et al., 2024; Kafando and Sakurai, 2025). In conjunction with the effects of climate change, such as persistent droughts and desertification, these conflicts further weaken the resilience of the Sudanese-Sahelian drylands (Jellason et al., 2021). In addition, reliable access to electricity is a major challenge across the region. Although some countries have made advances in recent years, access to electricity in rural areas remains highly unequal, and some populations still face considerable energy deficits (IEA et al., 2023). Energy poverty is linked to several socio-economic challenges, including limited access to education and healthcare (Sule et al., 2022). Furthermore, transportation limitations, inadequate information and communication technology infrastructure, and poverty hinder educational attainment in rural regions (Agyekum, 2023; Baffoe et al., 2021).

In summary, West African countries face numerous challenges with regard to sustainable development. Likewise, it is important to recognize the diverse realities within West Africa. Not every region is equally vulnerable, and there is also potential for growth and innovation (Adomako, 2020). Recognizing this potential requires implementing appropriate, context-specific policies that address current vulnerabilities and future challenges at a local level. These efforts must consider how the local population responds to the pressure described. This includes migration, which is one of many adaptation strategies.

1.2 Migration as adaptation for rural livelihoods in West Africa

The concept of migration as adaptation refers to the intentional, voluntary movement of individuals or groups as a proactive strategy to cope with environmental change, economic hardship, and socio-political challenges. This enables individuals to strengthen their economic situations, reduce risks, and build resilience. Rather than being seen solely as a response to crisis, this concept emphasizes the agency of migrants and the potential of migration to enhance adaptive capacity (Black et al., 2011a; Sakdapolrak et al., 2024a; Scheffran et al., 2012).

In West Africa, migration has long been an important livelihood strategy. Rural populations often rely on seasonal or long-term internal or cross-border migration as one of several adaptation strategies to diversify income sources or reduce their vulnerability to environmental variability (Longueville et al., 2020; van der Land et al., 2018; Wiederkehr et al., 2018). While Hoffmann et al. (2022) view migration as a complementary approach to other adaptations, like crop management, depending on local socio-economic conditions, Vinke et al. (2020) argue that migrants may experience negative socio-economic and health consequences.

Remittances from migrants often provide financial support to families in their regions of origin, allowing them to invest in basic needs such as food, housing, and education, and to adapt to changing climatic conditions (Adaawen and Owusu, 2013; Bosetti et al., 2021). However, communities may become overly reliant on remittances from migrants, which can create financial insecurity if those income streams are interrupted (Savage and Harvey, 2007). Not all populations have the resources or social networks to migrate, leading to "trapped populations" that remain vulnerable to environmental shocks (Osei-Amponsah et al., 2023).

While migration can be an adaptive strategy, it also introduces a range of challenges that can undermine its potential benefits. Hermans et al. (2023) show complex, reciprocal relationships rather than simple causal links between environment and migration. Environmental changes can trigger out-migration, particularly through declining agricultural production and food insecurity. On the other hand, in-migration can impact receiving areas through land use changes and potential resource conflicts. For example, migration movements in Burkina Faso have increased the pressure on land resources, which has led to accelerated degradation in both the areas of origin and destination (West and Nébié, 2019). Similarly, in Nigeria's savannah region, in-migration has been associated with several land degradation processes, including deforestation, soil depletion, and unsustainable land use practices (Aweda et al., 2024).

Migrant flows into urban centers or resource-rich areas can lead to overcrowding and the expansion of informal settlements. Rapid urban population growth often outpaces infrastructure development, increasing vulnerability to climate extremes and heightening demand for water resources (Kassouri, 2021; Ofoezie et al., 2022). Increased pressure on urban infrastructure is causing environmental degradation and growing pressure on natural ecosystems, including pollution, deforestation, and biodiversity loss in destination areas (Akubia et al., 2020; Herrmann et al., 2020; Kyere-Boateng and Marek, 2021; Scheffran et al., 2012). For example, in Ghana, deforestation is further exacerbated by both legal and illegal gold mining activities, commonly known as galamsey, which also contribute to soil degradation and deteriorating water quality (Awotwi et al., 2018; Gbedzi et al., 2022). In Ghanaian and Nigerian cities like Accra and Lagos, in-migration contributed to the expansion of densely populated urban areas with a lack of adequate housing, poor access to basic services, and insecure land rights (Aliu et al., 2021; Harris, 2021). Internal migrants and return migrants have higher mortality risks compared to permanent residents, with females particularly disadvantaged (Ginsburg et al., 2021). Women migrants working in the informal sector are often excluded from the health system (Lattof et al., 2018). Furthermore, migration can disrupt social ties and have a negative impact on mental health. Migrants may also be exposed to social isolation and marginalization in the area of destination (Sakdapolrak et al., 2024b; Torres and Casey, 2017). Nevertheless, migration can support sustainable transitions if it improves migrants' well-being without increasing social inequalities or environmental pressures (Adger et al., 2024). Therefore, it is important to visualize spatial patterns in order to better understand the complex relationships between vulnerability and migration and to be able to respond to them in a targeted manner.

1.3 Understanding past, present, and future migration patterns

1.3.1 Migration-related theories, frameworks, and definitions

Over the years, various migration theories and frameworks have been developed to explain the causes, patterns, and consequences of human mobility. Those relevant to this dissertation are described below in the order of their publication date.

In 1885, Ravenstein introduced the *Laws of migration* by analyzing internal migration within the United Kingdom and showed that migration followed certain patterns or "laws". Lee (1966, p. 50) expanded on Ravenstein's work by framing migration as a balance of push and pull factors between origin and destination. While "push" factors motivate individuals to leave their current location, "pull" factors attract them to new destinations. This theory, commonly known as *push-pull theory*, recognizes obstacles to migration, such as relocation costs and legal barriers. The push-pull theory is often used to analyze environmental migration, where environmental conditions can act as both push and pull factors. Additionally, it is employed to examine how environmental stressors interact with economic and demographic factors in migration processes (van der Geest, 2011). However, critics note that push-pull models oversimplify complex migration decisions and do not consider migration a process shaped by social factors (de Haas, 2021).

The Foresight conceptual framework, hereafter referred to as *Foresight framework,* depicts different drivers of migration (Foresight, 2011, p. 12). It serves as a conceptual tool for comprehending how environmental change impacts migration pathways. The framework, inspired by prior theories like push-pull, emphasizes that environmental change alone does not directly drive migration. The interconnected drivers operate across macro (e.g., economic, environmental, political, social, or demographic conditions), meso (e.g., institutional and policy frameworks), and micro (e.g., individual or household characteristics) levels. The framework illustrates how these factors interact to determine whether individuals or communities choose to migrate or stay. In particular, migration is conceptualized as a possible adaptive response to environmental stress and not merely a failure to cope. However, it has been criticized for oversimplifying migration as a mechanistic process and for a lack of explanatory power (Sherbinin et al., 2022).

Another framework, but not originally associated with migration, is the *IPCC risk framework*. McLeman et al. (2021) have applied this framework to climate-induced migration, proposing that migration may occur when communities reach critical thresholds of climate risk. According to the framework, which was first published in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014, p. 1046), climate risk is determined by three interrelated components: hazard, vulnerability, and exposure. When applied to migration, the framework illustrates how migration can be a response to risk, especially when climate hazards are exacerbated by vulnerability, exposure, and lack of adaptation.

The *aspirations-capabilities framework*, proposed by de Haas (2021, p. 25), is a comprehensive approach to understanding migration decisions that emphasizes the interplay between aspirations (or desires to migrate) and capabilities (or resources and means to migrate). The framework challenges the simplified view that economic incentives solely drive migration and acknowledges that a complex interplay of economic, social, cultural, and personal factors influences migration. For migration to take place, people must have the urge to move, and they must also have the necessary resources, networks, and information to make migration possible. Furthermore, individuals and households consider their desires and resources, as well as the available opportunities and constraints of potential destinations and areas of origin.

When analyzing migration patterns in West Africa, different types of migration must be recognized. Seasonal or permanent migration differs from forced displacement caused by severe drought, conflict, or terrorist attacks. People who want to migrate need financial resources. In other words, people without the required resources cannot migrate and thus remain in their current living situation. However, voluntary migration can also lead to insecure living conditions in the destination region and increase the vulnerability of migrants and their family members (Vinke et al., 2020). At the same time, not everyone desires to leave their place of origin, even if they have the means to do so and perceive external circumstances, such as climatic conditions, as unfavorable (Carling and Schewel, 2018; Schewel, 2020). Cross-border movement is facilitated by the ECOWAS (Economic Community of West African States) free movement protocols (Adepoju, 2003). It establishes the right of ECOWAS citizens to enter, reside, and pursue economic activities in member states. However, more than four decades after the protocols were established, mobility between regions remains restricted (Teye, 2022).

In this dissertation, the term "migrant" refers specifically to people who move within their country or across borders to neighboring countries, as this is the main type of migration in West Africa (McAuliffe and Ouch, 2024; Teye, 2022). Since this thesis involves environmental and climate changes, which are mostly impacting rural, agriculture-dependent populations, here, migrants are defined as individuals who move from rural to urban or other rural areas. Furthermore, rather than being seen as a generalized risk to be avoided, migration must be recognized in a differentiated way as a possible means of minimizing risk and increasing resilience. In this dissertation, migration is therefore seen not as a risk, but as a strategy, with different outcomes, depending on local conditions (see Chapter 1.2).

Another term that needs to be defined is "vulnerability". It generally refers *to "the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards"* (UN General Assembly, 2016, p. 24). In this dissertation, vulnerability is used to understand how certain populations, particularly rural communities, are exposed to and affected by multiple unfavorable factors. When referring in particular to the IPCC risk framework, vulnerability is defined as

"*The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt*" (IPCC, 2021a, p. 2253).

1.3.2 Measuring migration patterns

In this dissertation, migration patterns refer to the spatial dimension of human mobility, with a particular focus on areas of origin. But measuring migration is challenging due to the multitude of factors that impact migration decisions in West Africa (as described in Chapter 1.1). Since for many countries, no current census data depicting migration movements is available, the data only relates to larger administrative units, or is not updated regularly (Contreras et al., 2020; Sherbinin et al., 2015), alternative methodologies must be used. One approach is to conduct interviews with individuals who are (potentially) migrants (Henry et al., 2003; Mattah et al., 2024), or with experts in the field (West and Nébié, 2019), to gain insights into the past and potential future motivations behind migration, the places of origin, and the potential destinations. As these studies are very resource-intensive and draw mostly on small sample sizes, it is important to know the factors that influence migration decisions to be able to use alternative data sources. In this way, migration patterns can be approximated by examining the causes or consequences of migration linked to external factors, such as changes in land cover, infrastructure development, or environmental conditions.

Many studies, for instance, employ remote sensing techniques and geospatial data to measure migration. This also makes data available in regions that are conflict-prone or otherwise inaccessible. For example, land use and land cover change (LULCC) mapping using satellite data can help to monitor out-migration from areas where declining agricultural land and food insecurity are causing people to leave (Okeleye et al., 2023). On the other hand, it can assess the impacts of in-migration on destination areas, such as land conversion for housing and infrastructure (Kutir et al., 2022). In addition, analyzing urbanization trends enables the identification of changes in the size and distribution of urban and rural settlements over time (Asabere et al., 2020), which can be attributed to migration from rural to urban areas. As natural population growth also contributes to urbanization, and it is often challenging to distinguish between the various contributing factors, it is not appropriate to attribute urbanization solely to migration (Bocquier et al., 2023).

In societies reliant mainly on agriculture, like those in West Africa, climate data and other environmental indicators can be used as proxies for examining hazards that impact communities. Due to the high spatial and temporal resolution of these data sets, it is possible to estimate historical and future trends and thus conduct risk assessments in connection with droughts, floods, and declining agricultural productivity. Further environmental aspects, like land degradation (Hitzhusen, 1993), soil moisture (Ding and Xu, 2023), and soil fertility (Kopittke et al., 2019), are also vital for explaining variations in agricultural output. However, while climate data are available over large temporal scales and for the future, land degradation and soil fertility data typically are not.

As outlined in Chapter 1.1, migration is influenced not only by environmental factors but also by socio-economic conditions. Recently, the availability of socio-economic data has expanded, including night-light data, which are used as a proxy for economic activity (Pérez-Sindín et al., 2021). Additionally, gridded population data is available for historical time periods and the future, allowing for the description of demographic change (e.g. Wang et al., 2022). However, it should be noted that the majority of the socio-economic data, such as access to education or access to roads, has limited temporal resolution. These factors are generally only available for a specific time period and can hardly be predicted for the future. When measuring socio-economic factors with spatial data, the focus is on broader structural factors such as access to infrastructure, access to education, employment, and poverty, rather than individual socio-demographic characteristics such as age or gender (Sherbinin et al., 2015).

Though not assessed in more detail in this dissertation, a recent approach to include the rather young and urban migrant perspective is to use geolocated tweets from the microblog X (formerly Twitter) (Mast et al., 2024). This approach allows for a large-scale analysis of migrant interests, particularly in urban environments. Whether and how this specific data can be used in the future in academia is questionable, as X now charges for the use of tweets and is known to spread disinformation alongside allowing bots to register as users (Murthy, 2024).

In recent years, spatial analysis has increasingly been used to map vulnerability to environmental hazards, like floods (Li et al., 2022; Tetteh et al., 2024) or droughts (Durowoju et al., 2022). While climate-related vulnerabilities in Africa have been widely examined (Schneiderbauer et al., 2020; Sherbinin et al., 2015), few studies have specifically connected these evaluations to migration patterns. Detailed socio-economic data and recent official migration statistics, such as those currently available for Ghana (GSS, 2023), have not been comprehensively integrated into existing migration research. Research on current migration has mostly focused on environmental or demographic factors (Bruin et al., 2022; Hermans-Neumann et al., 2017; van der Geest, 2011).

Future migration patterns are difficult to predict, mainly because of their underlying drivers (see Chapter 1.1), especially those that could change suddenly (like flood events or conflicts). Climate change adds further uncertainty, as its impacts depend on variables such as technological advances or adaptation efforts (IPCC, 2022). Recent studies have applied diverse models, including gravity, radiation, agent-based, and statistical approaches to predict climate-induced migration (Schewel et al., 2024). Some rely on quantitative modelling to project trends, while others use scenarios to explore possible outcomes (Amakrane et al., 2023; Rigaud et al., 2021). These approaches aim less at predicting exact numbers and more at capturing the wide range of ways migration could evolve in response to social, economic, political, and environmental pressures. For climate-induced migration, these models combined environmental variables (e.g. temperature rise) with nationwide socio-economic indicators (e.g. national Gross Domestic Product (GDP)). Future projections of climate and population are often based on Representative Concentration Pathways (RCPs), which outline greenhouse gas concentration trajectories, and Shared Socioeconomic Pathways (SSPs), which describe alternative scenarios of societal development (Schewel et al., 2024, Wang et al., 2022). Nevertheless, while migration prediction models are becoming more advanced, they are best used as tools to explore possible scenarios rather than provide precise forecasts. This is because, at this stage, available models differ widely in their estimates and cannot predict future migration reliably (Schewe and Beyer, 2025; Schewel et al., 2024; Valk et al., 2022).

The complexity of migration makes it difficult to capture using a single method or data source (Neumann and Hilderink, 2015). Instead, migration research benefits from a multi-dimensional approach that integrates environmental, socio-economic, and demographic data. This combination of perspectives allows for the identification of underlying patterns and the estimation of future migration patterns with higher accuracy. However, integrating these diverse data sources also presents challenges, such as differences in temporal and spatial resolution, potential biases, and the (un)availability of key variables (Helbling et al., 2023; Niva et al., 2021). Overall, there have been few attempts to connect current and future socio-economic and environmental vulnerability, which involves mapping the combined effects of adverse environmental and socio-economic factors, with the measurement of migration at the local level using high-resolution data.

2 Objectives and structure of the dissertation

This dissertation examines the multiple and interrelated factors that influence migration in West Africa. The focus is on identifying areas from which out-migration has occurred in the past and where migration is most likely to take place in the present and future. It is structured around three interconnected studies, each contributing to a broader understanding of migration patterns in West Africa, with a focus on Burkina Faso, Nigeria, and Ghana. The central objectives that link the three publications are as follows:

1. Identifying the main factors influencing migration in West Africa, with a particular emphasis on populations dependent on agriculture.
2. Determining where these factors influencing migration are most prevalent by analyzing their spatial distribution across Burkina Faso, Nigeria, and Ghana.
3. Applying geospatial methods to analyze and map spatially available indicators as proxies for factors influencing migration and assess their relevance for understanding past, current, and potential future migration patterns, particularly to identify areas with a higher likelihood of out-migration.

The first publication (hereafter referred to as Study 1) is the basis for the dissertation, as it identifies the causes of past migration and outlines historical migration routes in West Africa (Chapter 4.1).

I. Schürmann, A., Kleemann, J., Teucher, M., Fürst, C. and Conrad, C., 2022.
Migration in West Africa: a visual analysis of motivation, causes and routes.
Ecology and Society, 27(3). https://doi.org/10.5751/ES-13489-270316

It provided a comprehensive overview of case studies from the literature on past origin and destination areas of migration in West Africa. This information was used to map migration drivers and routes within the push-pull theory, visually representing relationships between push and pull factors by thematic maps. The study aimed to make complex migration patterns more accessible to policymakers and the scientific community, as previous studies have often presented reasons for migration without spatial context.

Building on the factors identified in Schürmann et al. (2022), the second publication (hereafter referred to as Study 2) examined the use of geospatial data as proxy indicators, applying a weighted overlay approach to determine socio-environmental vulnerability in Ghana (Chapter 4.2).

II. Schürmann, A., Kleemann, J., Teucher, M. and Conrad, C., 2024.
Mapping socio-environmental vulnerability to assess rural migration in Ghana.
Applied Geography 167, 103283. https://doi.org/10.1016/j.apgeog.2024.103283

This study identified rural areas in Ghana where out-migration is currently likely due to the co-occurrence of multiple adverse environmental and socio-economic factors, weighted through expert interviews. Bivariate maps illustrated areas where the impact of factors coincides with high population density. Unlike recent studies that focused primarily on environmental or demographic factors at broader spatial scales, this approach provides a more localized and comprehensive assessment of vulnerability mapping.

The third publication (hereafter referred to as Study 3) complements the first two publications by incorporating climate projections to estimate migration as a response to environmental hazards and socio-economic vulnerabilities (Chapter 4.3).

III. Schürmann, A., Teucher, M., Kleemann, J., Inkoom, J. N., Nyarko, B. K., Okhimamhe, A. A., Conrad, C., 2025. Spatial assessment of current and future migration in response to climate risks in Ghana and Nigeria. Frontiers in Climate 7. https://doi.org/10.3389/fclim.2025.1516045

The study used a risk assessment framework to evaluate potential current and future migration patterns in Ghana and Nigeria. This approach fills a critical gap because there are still few spatially explicit estimates of how future climate conditions, socio-economic vulnerabilities, and population density will interact and potentially influence the likelihood of out-migration.

Moreover, a further publication was developed, which is not part of the main body of the dissertation and is not discussed in detail. It shifts the focus from the factors that drive migration to the environmental impacts of in-migration, thereby expanding the scope of the aforementioned studies. It analyzed how migration causes land degradation in Nigeria's Savannah region and builds, among others, on insights gained in Study 1, which were incorporated into the publication's introduction section.

Aweda, E.D., Okhimamhe, A.A., Obateru, R.O., Schürmann, A., Teucher, M., Conrad, C., 2024. Assessing the Impacts of Migration on Land Degradation in the Savannah Region of Nigeria. Sustainability, 16(18), 8157. https://doi.org/10.3390/su16188157

This study combined remote sensing data with findings from community surveys and focus group discussions. It indicated that migration-induced urban expansion and deforestation contribute to land degradation in the studied region and highlighted the need to incorporate community perceptions into sustainable land management strategies.

The structure of the dissertation is as follows: Chapter 1 presents the theoretical background, describing the environmental and socio-economic challenges in West Africa and the role of migration as an adaptation strategy. It also explores how past, present, and future migration patterns can be measured. Chapter 2 describes the objectives and the interlinkage between the three studies as well as the structure of the dissertation. Chapter 3 outlines the methodological approach, including the study area, the data used, and the applied methods for mapping vulnerability and assessing potential out-migration. Chapter 4 contains the three main studies that examine migration in the past, present, and future. The discussion in Chapter 5 critically evaluates the findings, outlines local policies to reduce the need for migration, and reflects on the theories, frameworks, and methods applied. Chapter 6 offers directions for future research, and Chapter 7 provides a conclusion that summarizes the main outcomes.

3 Overview of materials and methods

3.1 Study area

The study area covers Burkina Faso, Nigeria, and Ghana, three West African countries characterized by diverse environmental and socio-economic conditions and challenges, as described in Chapter 1.1. Understanding their demographic, economic, and agricultural profiles is essential for analyzing the drivers of migration in the region. Although they are geographically close, these countries differ in climatic conditions, land use, and demographic characteristics. Figure 3.1 shows the location of the focus countries as well as the respective geographic focus of the three studies.

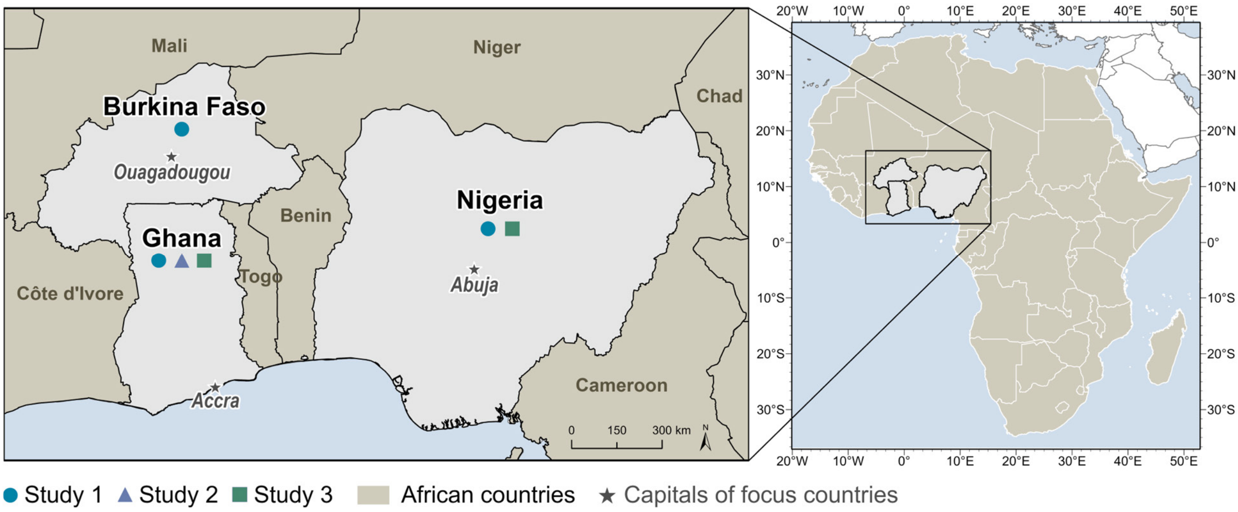

Figure 3.1 *Location of the focus countries, Burkina Faso, Nigeria, and Ghana, within Africa. The different symbols visualize the geographic focus of the three publications. Study 1 = Schürmann et al. (2022), Study 2 = Schürmann et al. (2024), and Study 3 = Schürmann et al. (2025).*

Nigeria is the most populous country in Africa, with an estimated population of 232.7 million in 2024. Burkina Faso has a population of 23.5 million and Ghana has a population of 34.4 million, respectively (UNDESA, 2024). The proportion of rural population is high across all three countries, as in 2023, 67.5% of Burkina Faso's population, 40.8% of Ghana's, and 45.7% of Nigeria's lived in rural areas (World Bank, 2025).

Figure 3.2 shows that annual precipitation generally increases from north to south across the study region. Northern Burkina Faso and Nigeria (Sahel Zone) receive less than 600 mm of rain annually, in a short rainy season. Here, farmers grow drought-tolerant crops such as millet and sorghum (Sanou et al., 2023). Further south, central Ghana and Nigeria are located within the Guinea savannas, which receive 1000-1200 mm of rainfall annually. These zones support mixed cropping and low-density tree cover, with crops like maize, millet, and guinea-corn (Aniah et al., 2019). The highest rainfall occurs in southern Ghana and Nigeria, with amounts reaching more than 1,600 and 2,000 mm annually, respectively. In contrast, the coastal zone of Ghana, including Accra, receives 800-1000 mm annually. Southern parts of Ghana and Nigeria are characterized by a biannual rainfall regime, influenced by the annual movement of the Inter-Tropical Convergence Zone (ITCZ) (Dunning et al., 2016). Crops such as cassava, plantain, and yam, and cash crops such as cocoa and oil palm are grown (Acheampong et al., 2023; Amuda and Alabdulrahman, 2024). In general, the south of the study area is highly urbanized (see built-up area in Figure 3.2).

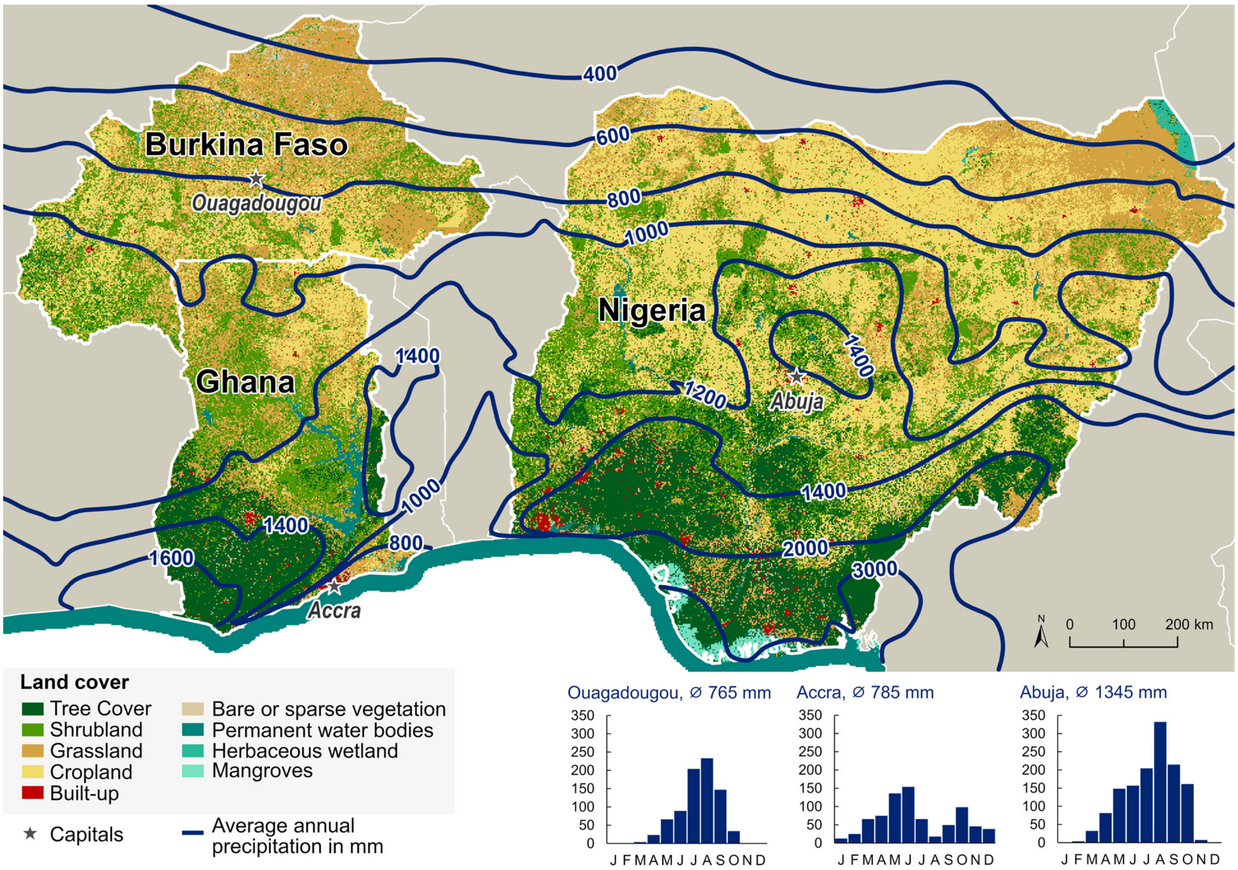

Figure 3.2 *Map of focus countries with average annual rainfall, monthly rainfall distribution for the capital cities, own calculations based on Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) (1994-2023), and land cover for the year 2020 (Zanaga et al., 2021).*

Cropland is a major land cover type, covering about 76% in Nigeria, 55% in Ghana, and 53% in Burkina Faso. While the proportion of people working in agriculture has declined slightly in recent years, the sector employs a large share of the labor force in 2023: 35.4% in Ghana, 34.3% in Nigeria, and 31.4% in Burkina Faso (World Bank, 2025).

Access to infrastructure varies widely across the three countries. In 2022, 71.6% of Ghana's rural population had access to electricity, compared with 27% in Nigeria and 3.4% in Burkina Faso. Education levels show a similar divide: while 87.1% of adults in Nigeria and 64.9% in Ghana had completed at least primary school, the figure was 24.9% in Burkina Faso (World Bank, 2025). Furthermore, Nigeria and Burkina Faso also face security threats from extremist groups, which have led to large-scale displacement (George and Adelaja, 2022; Okafor et al., 2023).

3.2 Mapping of vulnerable areas to assess migration

The methodology applied in this research follows a mixed-methods approach, combining literature review, expert interviews, and geospatial analysis techniques to assess migration. This combination provides a nuanced understanding of where individuals and communities are likely to decide to migrate in response to unfavorable environmental and socio-economic factors. Figure 3.3 provides a general overview of the workflow, indicating which methodological approach was used in each study and the respective time scales addressed. The research is based on a literature review (Chapter 3.2.1), which serves as a basis of knowledge and constitutes the main body of Study 1. Expert interviews were conducted in studies 2 and 3 to evaluate factors influencing migration tailored to the respective focus countries (Chapter 3.2.2). The identified factors were proxied using multiple spatial datasets (Chapter 3.2.3), combined and integrated with different spatial techniques (Chapter 3.2.4), and subsequently visualized (Chapter 3.2.5). Finally, the results were analyzed for plausibility (Chapter 3.2.6).

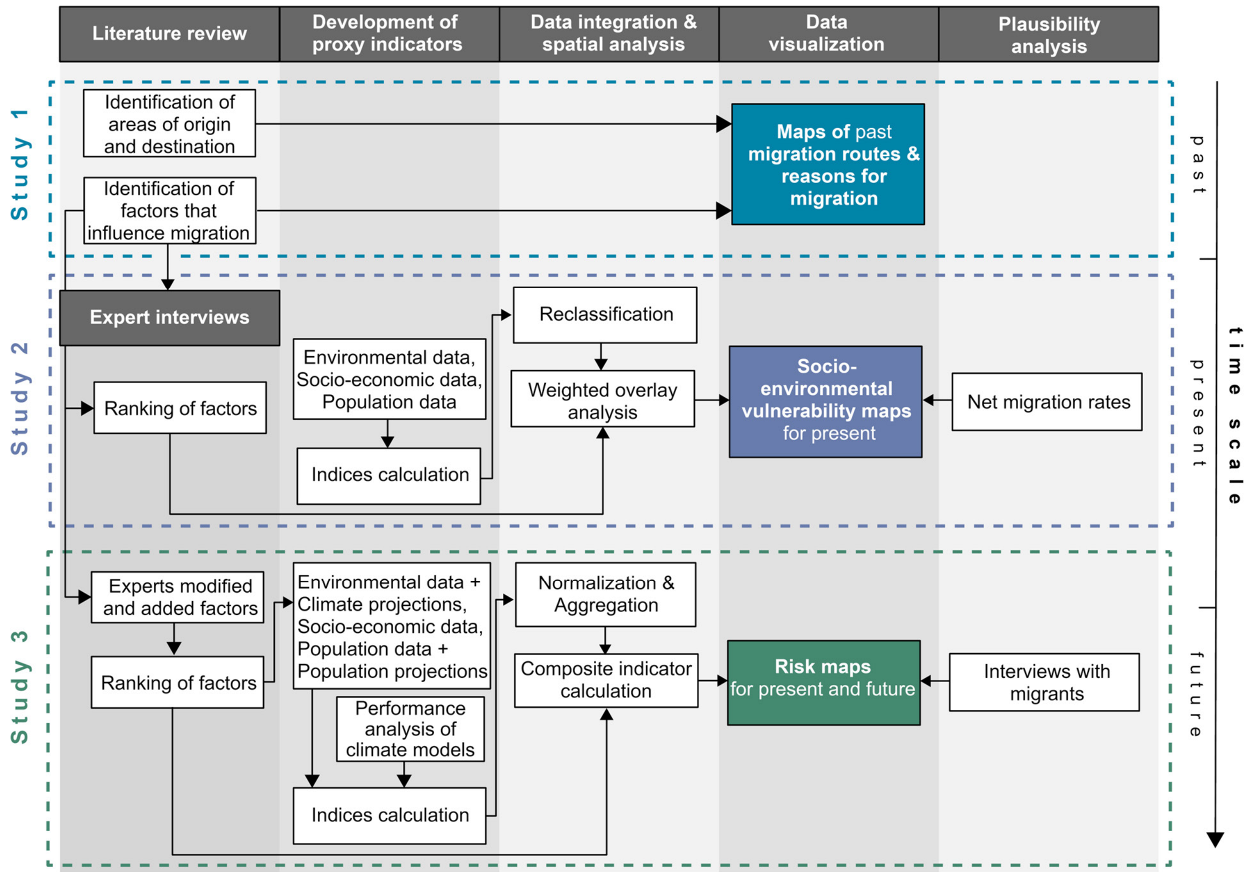

Figure 3.3 *Overview of the general workflow in this dissertation. It displays the six main methodological steps (dark gray boxes) applied across the three studies.*

3.2.1 Literature review

In order to gain a comprehensive understanding of existing research on migration in West Africa, a structured literature review was conducted. The methodology for this review, including the specific keywords, is detailed in Chapter 4.1 (Schürmann et al., 2022). The review focused on factors migrants identified as having influenced their decision to migrate. Only case studies based on direct interviews were included. While the terms “push” and “pull” did not have to be explicitly used, the underlying reasons related to origin or destination had to be clearly stated. The identified factors form the basis for the subsequent methodological steps.

3.2.2 Expert interviews

Experts in migration-related fields were interviewed to assess the factors identified in the literature review. These interviews aimed to evaluate and rank the factors that affect migration choices, utilizing the practical experience and local knowledge of the experts. Table 3.1 shows further characteristics of the expert interviews.

Table 3.1 *Key characteristics of conducted expert interviews. Details on the expert’s affiliation and expertise are provided in Schürmann et al. (2024; 2025).*

	Study 2	**Study 3**
Aim of the interviews	Ranking of factors influencing migration in Ghana, with a focus on the rural population	Ranking of factors within a risk assessment framework (hazard, vulnerability, exposure) for Ghana and Nigeria
Number of experts	15 (from Ghana)	4 (from Ghana), 6 (from Nigeria)
Date of interviews	March and April 2022	November and December 2023
Mode of interview	In-person interviews in Accra, Kumasi, and Cape Coast	Online workshops (using the Miro Board (www.miro.com)
Interview structure	Questionnaire with predefined factors influencing migration derived and adapted from the literature review (Schürmann et al., 2022)	Predefined factors from the literature review were embedded in an impact chain based on the IPCC risk framework, visualized in the Miro Board. Experts were allowed to modify, add, and remove factors
Ranking method	Likert scale rating (Likert, 1932)	Budget allocation method (European Commission, 2023)

3.2.3 Collection of spatial data and development of proxy indicators

For each factor identified in relevant literature and expert interviews, suitable spatial proxy indicators have been sought to represent that factor most appropriately. Spatial data was separated into three groups, namely environmental data (including climate data), socio-economic data, and population data.

Climate data were used to model historic and future precipitation, temperature, and wind speed. Historical precipitation patterns (time period 1991-2021 for Study 2 and time period 1994-2023 for Study 3) were analyzed using the Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS), a high-resolution precipitation dataset suitable for areas with inadequate ground-based measurements (Funk et al., 2015). Data on historical temperature and wind speed were obtained from the ECMWF Reanalysis v5 (ERA5), the fifth-generation atmospheric reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2018). Future climate projections are based on the Coupled Model Intercomparison Project Phase 6 (CMIP6) ensemble, with the RCP4.5 scenario chosen due to its applicability to actual policy situations (Zebisch et al., 2023). This pathway illustrates an intermediate scenario where moderate mitigation efforts lead to a temperature rise of 2-3°C by the year 2100 (IPCC, 2021b). Thirteen CMIP6 models were tested on their performance, as measured by the mean absolute error (MAE) (Willmott, 1982) and the Kling-Gupta efficiency (KGE) (Gupta et al., 2009). All data were harmonized to 1° resolution using bilinear interpolation. Finally, ensemble means were calculated for the selected models to reduce model-specific biases.
Several climate indices were calculated from historical and projected datasets to investigate the effects of regional climate on agriculture. For instance, the onset of the rainy season was determined pixel-by-pixel for every year within the time period under consideration. The different approaches used to calculate the rainy season are described in detail in the respective studies (Chapter 4.2 and 4.3). Additional indices were derived, for example, consecutive dry days, hot days, and maximum wind speed. Predictive models were calculated using the delta method (e.g. Hay et al. (2000) or Hawkins et al. (2013), where the mean difference between future climate indices (2021-2050) and historical climate indices (1994-2014) was added to the present-day observational baseline (1994-2023, CHIRPS and ER5).

In addition to climate data, other environmental data that have an impact on the agricultural-dependent population were analyzed. These include land degradation, which was assessed using changes in the Normalized Difference Vegetation Index (NDVI) derived from Moderate Resolution Imaging Spectroradiometer (MODIS) data. NDVI trends provided information on vegetation conditions and land productivity, which are often closely linked to agricultural livelihoods in the study area (Knauer et al., 2014). Moreover, the frequency of fire events was calculated using MODIS data, revealing patterns that could disrupt agricultural activities (Dahan et al., 2023).

Socio-economic factors are key contributors to migration decisions in the study area. For Ghana, the 2021 Population and Housing Census (PHC) provided information on variables at the district and regional levels, such as access to education or microcredit institutions, as well as the unemployment rate. The tabular data from the PHC was spatially processed by assigning the information to the district or region. Efforts were made to obtain comparable socio-economic data for Nigeria to enable cross-country analysis. However, as there is no current census, it was necessary to receive data from other freely available datasets such as the Demographic and Health Surveys Program (DHS) or the Centre for International Earth Science Information Network (CIESIN).

To calculate the affected population in Study 2, data provided by the Global Human Settlement Layer (GHSL) were used, and WorldPop data were selected to visualize population density (Schiavina et al., 2023; WorldPop and Bondarenko, 2020). In Study 3, current and future population densities and the distribution of population were calculated based on population data published by Wang et al. (2022). In addition, these data were evaluated to assess the exposure level of different population groups.

3.2.4 Data integration and spatial analysis

This chapter describes the methods for further processing and integrating proxy indicators into various spatial analyses. Figure 3.4 shows the migration theories and frameworks (described in Chapter 1.3.1) used in each study to structure and interpret the assessment of factors influencing migration.

	Study 1	Study 2	Study 3
Push-pull theory	Directly applied		
Foresight framework	Indirectly applied		
	Used as conceptual basis for selecting and categorizing factors influencing migration	Indirectly applied through the factor selection based on Study 1	Indirectly applied through the factor selection based on Study 1
Aspirations-capabilities framework		Recognized as relevant but not directly applied	
IPCC Risk framework			Directly applied

Figure 3.4 *Overview of applied theories and frameworks across the three studies.*

The push-pull theory was applied to analyze factors influencing past migration and the spatial relationships between areas of origin and destination. Migration factors were manually extracted from case studies identified through a systematic literature review (Chapter 3.2.1). According to the Foresight framework, these drivers and factors were then categorized as environmental, economic, demographic, social, or political drivers. Food security was included as an additional category (Neumann and Hermans, 2017). Each factor was classified as either a push or pull factor, distinguishing between conditions that motivate migration and those that attract migrants.

For the spatial socio-environmental vulnerability assessment, proxy indicators with trend data, mean, and trend layers were combined and reclassified into new composite indicators. All datasets were reclassified to a common scale using natural breaks for consistency and converted into raster format. The proxy indicators were combined and integrated into the Weighted Overlay Analysis (WOA) tool in ArcGIS Pro. The weightings derived from the Likert scale were converted into values between 1 and 100 using the Relative Importance Index (RII) to ensure their usability in the WOA.

The IPCC risk framework was used to assess current and future climate risks using a different integration of indicators with normalized and weighted aggregation methods. All indicators were rescaled to a common 0.0–1.0 range (GIZ and EURAC, 2017). The data were aggregated at administrative level 2, which corresponds to districts in Ghana and local government areas (LGAs) in Nigeria. Where future projections were available (for the hazard and exposure component), global normalization was used across time periods to ensure comparability. Weights adjusted by experts were applied to reflect future relevance. Composite indicators were calculated using weighted arithmetic aggregation (Zebisch et al., 2023).

3.2.5 Data visualization

The factors that have historically influenced migration were summarized in frequency matrices for Burkina Faso, Nigeria, and Ghana. Sankey diagrams were used to illustrate the connections between the areas of origin and destination and the related factors. The areas were georeferenced based on recorded locations. ArcGIS Pro was used to locate push and pull factors, with infographics showing thematic drivers and directional arrows displaying migration routes.

The results of the WOA were visualized in impact maps to identify current socio-environmental vulnerability patterns for Ghana. These included separate maps for environmental and socio-economic factors, as well as a map where these factors are combined. In order to illustrate both the vulnerability and the exposure of the population, bivariate maps were created that overlaid the impact of the factors with the population density.

Normalized composite indicators were used to create hazard, vulnerability, and exposure maps as well as overall risk maps that represent current and future conditions for Ghana and Nigeria. Change maps highlighted spatial changes in risk levels between the current and future, providing a clear view of areas likely to experience increased or reduced risk over time.

3.2.6 Plausibility analysis

The plausibility analysis entailed a thorough examination of the results from the socio-economic and environmental impact maps (Study 2) and the risk maps (Study 3). This evaluation process involved linking the results, or parts of them, with external, real-world datasets to ensure the spatial analyses were plausible. By comparing the results with observed data, it was determined how accurately the generated maps reflected actual conditions. For Study 2, a comparative analysis of net migration rates (2010-2021, GSS, 2023) and affected populations helped to evaluate whether vulnerable areas correspond to migration patterns. Plausible results were defined to occur when more than one-third of the rural population is located in vulnerable areas with negative migration (out-migration).

For Study 3, interview data from Nigeria (472 interviews) and Ghana (1,265 interviews) were used to determine whether hazard and vulnerability scores aligned with actual migration motivations and whether the findings were plausible. These surveys were conducted by research groups from the Federal University of Technology, Minna, in Nigeria, as well as the University of Cape Coast in Ghana, as part of the MIGRAWARE project (BMFTR, 2025), in which this dissertation is embedded. In addition, Ghana's net migration rates (GSS, 2023) were compared with risk scores, though similar data were not available for Nigeria.

4 Publications

4.1 Migration in West Africa: a visual analysis of motivation, causes and routes

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Overall aim:

To synthesize and visualize the interplay of different drivers and factors influencing past migration in West Africa, with a focus on Burkina Faso, Nigeria, and Ghana.

Methodology:

Twenty-six survey-based case studies were analyzed applying the push–pull theory. Sankey diagrams and thematic maps illustrate migration routes and the underlying factors.

Key findings:

- Environmental and economic factors are the primary drivers of migration and are often interrelated.
- In approximately 75% of cases, multiple push factors influenced migration decisions.
- Sankey diagrams revealed that destination areas are not merely the inverse of origin areas in terms of push–pull factors.

Relevance to dissertation objectives:

The study provided a more nuanced understanding of past migration patterns. It contributed to achieving objective 1 by giving an overview of the factors that influenced migration decisions in the past. It addressed objectives 2 and 3 by allocating push and pull factors to destinations and areas of origin. Furthermore, the study demonstrated that spatial mapping of past migration patterns is valuable for current policy planning. It can support sustainable development strategies, such as land management and SDG monitoring, by enabling region-specific, targeted measurements based on historical trends.

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Synthesis

Migration in West Africa: a visual analysis of motivation, causes, and routes

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ABSTRACT. Migration in West Africa has been taking place for centuries for different reasons. Many dimensions of migration remain insufficiently documented and poorly understood. In particular, factors of migration in destination areas and areas of origin are still lacking comprehensive analysis. In this paper, we bring a new perspective to the model of push and pull factors of migration in West Africa by reviewing and analyzing interview-based case studies of migration related to Ghana, Burkina Faso, and Nigeria, as well as to the associated migration routes. The overall aim of this study was to determine the areas that individuals historically chose as destinations for migration and what they perceived to be the distinctive conditions in those areas. Hence, characteristic features about destination areas and areas of origin were identified and located in maps, whereas interrelationships among push and pull factors were illustrated by means of Sankey diagrams. With these tools, we provide a novel combination for visualizing the reasons for migration. The literature review emphasizes the complex relationships between different drivers of migration, with environmental and economic factors emerging as the most important drivers of migration in the focus countries. Moreover, the identified and mapped migration patterns suggest that individuals migrate mainly from the northern part of a particular country to its center or southern regions. This scientific approach shows that the spatial allocation of migratory movements can facilitate assessments on how to meet specific Sustainable Development Goals and to improve regional policies.

Key Words: *area of origin; causes; destination area; drivers of migration; map; migration flows; migration patterns; push–pull model; Sankey diagrams; Sustainable Development Goals; review*

INTRODUCTION

The first objective of the UN's Sustainable Development Goals (SDG), namely to end poverty in all its forms everywhere, is merely one of many SDGs indirectly or directly related to forced and voluntary migration (UN 2015, IOM 2018). Although the goal is formulated globally, it is notably relevant to West Africa. In fact, this region is particularly vulnerable to multiple pressures such as climate change, low soil fertility, conflicts, and limited access to economic resources, all of which can lead to poverty and food insecurity (Mertz et al. 2011, Sissoko et al. 2011, Hollinger and Staatz 2015, Partey et al. 2018, Adaawen et al. 2019). Globally, migration has been a strategy for escaping poverty, food insecurity, or other adverse circumstances for centuries (Black et al. 2011b, Adger et al. 2018, Wiederkehr et al. 2018, Kumasi et al. 2019). Hence, migration can be seen as an adaptation strategy that assists households to diversify their income and decrease their exposure to climate change impacts, contributing indirectly to the achievement of SDG 13 (climate action; ODI 2018). However, voluntary migration can also entail insecure living conditions and accelerate vulnerability for migrants and their dependents (Warner and Afifi 2014, Vinke et al. 2020). Collecting data on migration-related issues corresponding to SDG 17.18, such as migration status or migration movements to and from rural areas, is essential for decision makers to create local, migration-sensitive policies (IOM 2018).

According to the United Nations Department of Economic and Social Affairs (UNDESA), an estimated 7.5 million migrants originated from West African countries in the year 2020. Approximately 89% of international migrants from West Africa stay in other West African countries (author calculations based on UNDESA 2020), indicating internal and cross-border migration patterns as the predominant phenomenon and characterizing the region as a hot spot for migration movements. The population in West Africa, consisting of a variety of ethnic groups, has migrated for many generations (Zachariah and Conde 1980, Bassett and Turner 2007). Ethnic groups like Fulani (Tonah 2002, Bassett and Turner 2007, Bukari et al. 2020), and Mossi (Skinner 1960, Henry et al. 2004, Kress 2006) are observed to be highly mobile throughout West Africa. When referring to human mobility in this region, it is important to differentiate various types of migration. Forced migration or displacement driven by severe droughts, conflicts, or terrorist attacks must be distinguished from seasonal (labor) migration (Adaawen et al. 2019). Other types of migration are outlined in the literature as long-term, short-term, and permanent migration (Guilmoto 1998, Bilsborrow and Henry 2012). As reported by the International Organization for Migration (IOM 2019), seasonal migration refers to migrant workers who depend on certain seasonal conditions and migrate for only a specific part of the year. Short-term migrants migrate for more than three months but less than 12 months, detached from seasonal conditions. Migrants who change their residence but intend to return after a limited period of time are termed as temporary migration. Long-term migration (also referred to as permanent migration in certain studies) is described as a change of residence of more than one year. Migration patterns in West Africa are sensitive to changing conditions (Dick and Schraven 2021), and usually occur in corridors from the more arid north to the more humid south of West Africa (Flahaux and de Haas 2016, van der Land et al. 2018).

The theoretical model of five drivers of migration, which include environmental, economic, demographic, political, and social forces (Black et al. 2011a), is used in a variety of literature (Parnell and Walawege 2011, Neumann et al. 2015, Neumann and

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Hermans 2017, de Longueville et al. 2020). Food security is considered as a sixth driver of migration in this study because it has been cited as an important factor of migration in a large number of studies that deal with migration in West Africa (Doevenspeck 2011, Pearson and Niaufre 2013, Sow et al. 2014, Neumann et al. 2015, van der Land et al. 2018, Morales-Muñoz et al. 2020). Moreover, given that food security is mostly a combination of several (negative) factors, such as armed conflict, low agricultural production, poor infrastructure, etc., assigning food security to one of the five drivers does not adequately and sufficiently address its importance.

The scientific discourse in recent years has focused on the influence of environmental change on migration patterns on account of the climate change debate (Brown 2008, Black et al. 2011c, McLeman 2013, Gautier et al. 2016, de Longueville et al. 2019, de Longueville et al. 2020, Rigaud et al. 2021). However, environmental factors must be integrated into a complex network of factors and processes and cannot be seen as a stand-alone determinant of migration (Bilsborrow and Henry 2012, Cattaneo and Massetti 2019, Adger et al. 2021). In particular, recent literature highlights the combination and interplay of several factors that influence the decision to migrate (Ackah and Medvedev 2010, Black et al. 2011a, Abu et al. 2014, Neumann et al. 2015, Sanfo et al. 2017, van Hear et al. 2018, Bukari et al. 2020). Economic and social factors play an important role when it comes to deciding whether to migrate or not (Carr 2005, Bassett and Turner 2007, Doevenspeck 2011, Sow et al. 2014). However, beyond a combination of factors that would be conducive to migration, the process also requires financial means. In other words, households that do not have the necessary resources may send only one household member or none to migrate, and thus remain trapped in their situation (Foresight 2011, Black et al. 2013, Cattaneo and Massetti 2019).

To further specify the reasons for migration, the model of push and pull factors (based on Lee 1966) is an approach that has been widely discussed in the literature (de Haas 2011, Parnell and Walawege 2011, Flahaux and de Haas 2016, Castelli 2018). Push and pull factors are seen as determinants of migration, with push factors being forces that pressure individuals to leave their place of origin, whereas pull factors induce people to move to a specific new place (Ackah and Medvedev 2010, Black et al. 2011c, Garcia et al. 2015, Sanfo et al. 2017, FAO et al. 2018). In this study the model of push and pull factors was used to retrieve information on destination areas and areas of origin, as these are essential for understanding migration patterns. Studies agree that migration in the region occurs mainly within the country or to neighboring countries (Adepoju 2003, Mercandalli and Losch 2017, van der Land et al. 2018, Adaawen et al. 2019). Ghana, Burkina Faso, and Nigeria were selected as focus regions in this study because they are of central importance for West African and North—South migration patterns (UNDESA 2019). Considering only international migration routes, according to estimations made by UNDESA, the main destination countries in 2019 for migrants from Burkina Faso were Côte d'Ivore, Ghana, and Mali. Migrants from Ghana moved mainly to Nigeria, Côte d'Ivoire, or Togo, and individuals from Nigeria especially migrated to Niger, Benin, or Ghana (UNDESA 2019). Although broad interregional and international migration corridors have been characterized in the literature (Mercandalli and Losch 2017, UNCTAD 2018, McAuliffe et al. 2019), the exact locations affected by out-migration or in-migration, especially in terms of within-country migration, still lack in-depth documentation.

Although several literature reviews or meta-analyses exist on the environmental influence on human mobility in West Africa (Jónsson 2010, Obokata et al. 2014, Gautier et al. 2016, Thober et al. 2018, Borderon et al. 2019), to date there is no scientific literature that specifically address reasons for migration in destination areas and areas of origins, nor scientific reviews that include a spatially explicit analysis of all possible driving forces in West Africa. In the studies published so far, the reasons for migration have mostly been presented in the form of text, tables, or bar charts (Ango et al. 2014, Olaniyan and Okeke-Uzodike 2015, Sanfo et al. 2016, Goldbach 2017, Neumann and Hermans 2017). The majority of studies have illustrated migration routes separately from the underlying factors (Henry et al. 2003, Rademacher-Schulz et al. 2014, Warner and Afifi 2014, Goldbach 2017). Paone and Richmond (2017) visualize both routes and reasons of migration, but focus exclusively on environmental factors.

In view of the above, our objectives in this paper are as follows:

- to ascertain and spatially allocate reasons for migration by analyzing survey-based case studies in the context of the previously described six drivers;
- to characterize destination areas and areas of origin by assigning respective push and pull factors in order to supplement the traditional push–pull model;
- to locate migration routes based on the conducted literature review; and
- to visualize the outcomes of the aforementioned objectives for a better understanding of migration patterns in the West African countries Ghana, Burkina Faso, and Nigeria

The results of this study will serve as groundwork for further research addressing the complex patterns of migration in West Africa and will facilitate the development of recommendations for regional policies.

METHODS

Study area

This study focuses on the three West African countries Ghana, Burkina Faso, and Nigeria (hereafter "focus countries") as important countries of an international collaboration to tackle challenges related to climate change and poverty (see West African Science Service Centre on Climate Change and Adapted Land Use [WASCAL], https://wascal.org/). For this study, emphasis is placed on English-speaking countries where UNDESA (2019) reports high migration rates (Sierra Leone, Liberia, and the Gambia report rather lower migration numbers). The selected countries are amongst the five most densely populated countries in West Africa (World Bank 2021). Given the substantial migration flows between Ghana and Burkina Faso and the availability of extensive literature on migration patterns in Burkina Faso, we have additionally included this country in our analysis. In addition, studies related to migration routes to or from the focus countries, such as Benin or Côte d'Ivoire, were analyzed. These countries differ not only in their economic situation, but

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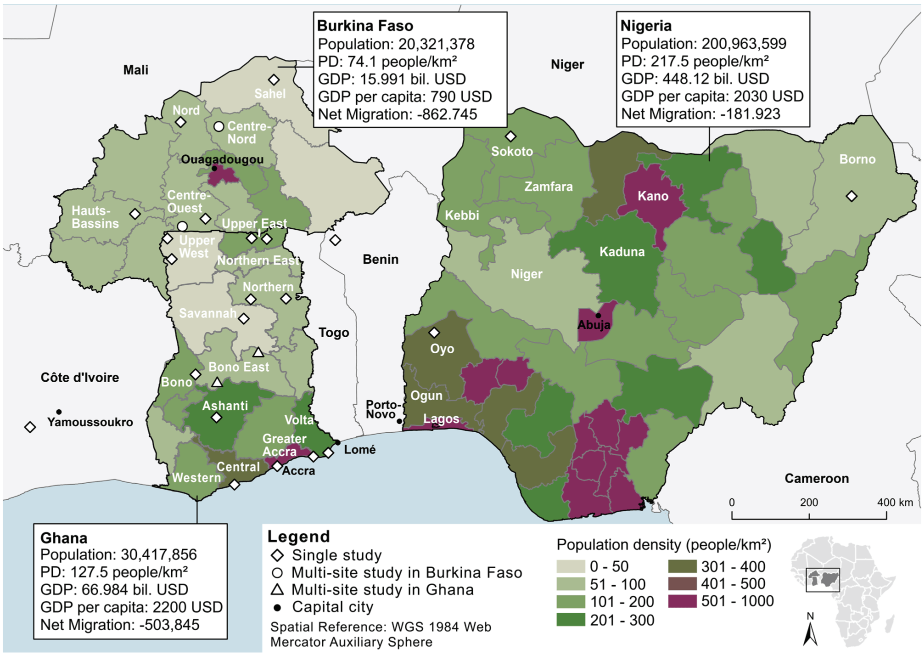
Fig. 1. The focus countries Ghana, Burkina Faso, and Nigeria with relevant socio-economic information, the districts of interest for this study, population density per district, and the location of the selected case studies. The data shown refer to the year 2019. Sources: UNDESA 2019, World Bank 2021; Humanitarian Data Exchange, https://data.humdata.org/; WorldPop, https://www.worldpop.org/project/categories?id=18.



also in their migration rates and population density, as illustrated in Figure 1. Nigeria and Ghana are anglophone countries and are similar in their gross domestic product (GDP) per capita, but total GDP in Nigeria is considerably higher (World Bank 2021). Although francophone Burkina Faso is the least densely populated country among the focus countries, it experiences the highest rate of out-migration (World Bank 2021; WorldPop, https://www.worldpop.org/project/categories?id=18). The focus countries cover several bioclimatic regions, ranging from the arid Sahel subregion in northern Burkina Faso to the humid Guinea-Congo subregion in southern Nigeria (Herrmann et al. 2020). The three focus countries are analyzed separately because of their different geopolitical and socio-economic backgrounds, but cross-border migration among them is analyzed together.

Selection of literature and location of case studies

With the aim of a comprehensive literature research, multiple keywords were selected, which are indicated in Figure 2. We used the search terms "migra*" or "human mobility" in combination with a keyword from the second and third box together with the respective country name or the term "West Africa." The definition of keywords is based on a previous literature review on the topic of migration in West Africa. Therefore, only keywords that have been identified in numerous studies as being associated with the term "migration" were applied. The search was conducted between March 2021 and June 2021 using the search engines Web of Science (https://apps.webofknowledge.com) and Google Scholar (https://scholar.google.com).

We additionally formulated several criteria for the selection of case studies in order to maintain quality standards and achieve our research objectives. To be included, a study had to fulfill the following criteria:

- qualitative or quantitative surveys carried out by the authors of the case studies (literature reviews or studies that only processed census data were excluded);
- published in a journal with peer-review process;
- published in the English language;
- published in the last 20 years;
- defined destination areas and areas of origin of migrants; and
- defined push and pull factors.

The terms "push" or "pull" did not necessarily have to be used in the studies but rather the reasons related to the destination area or area of origin had to be mentioned. In the end, 24 scientific papers were included. Of these, 14 pertain to Ghana, six to Burkina Faso, and four to Nigeria. In two of the studies, multiple sites were evaluated. These were counted separately because all the above-mentioned criteria apply, resulting in a total of 26 case studies for the analysis. Certain studies that did not meet all criteria have been excluded from the analysis but serve as supporting literature for the discussion. An overview of all case

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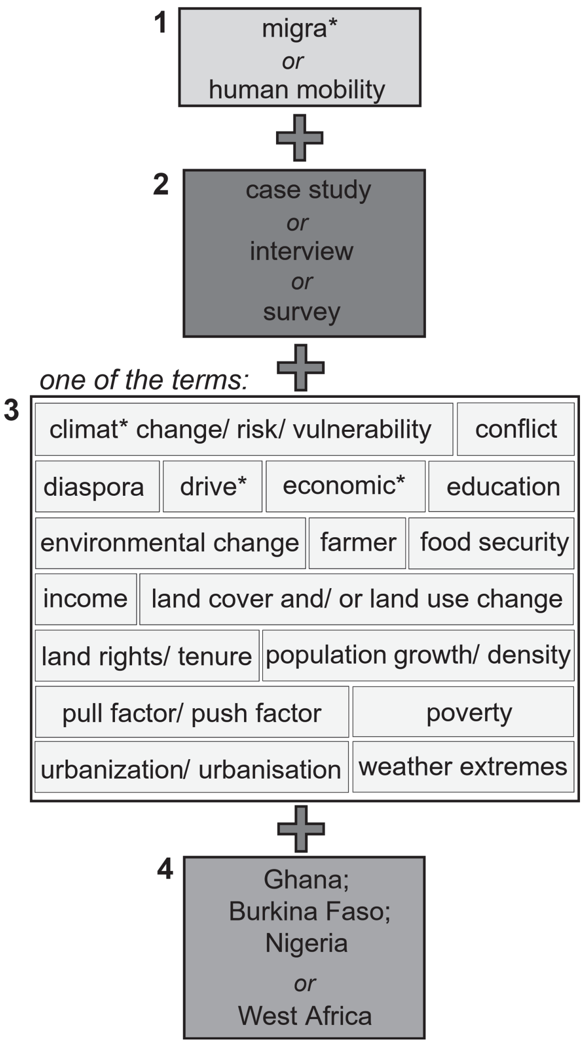
Fig. 2. Overview of keywords for case study selection.



studies is provided in Appendix 1 (Table A1.1). The respective location of case studies in West Africa can be found in Figure 1. Table A2.1 in Appendix 2 lists the references that were found on Web of Science prior to applying the criteria for case study selection, but were not included in the underlying analysis.

Analysis of literature according to push and pull factors of migration

For the most part, factors were included in the analysis that were reported in the methods or results section of the respective study, in other words, factors that were mentioned by the respondents. Some of the factors, however, came from third sources, but were supported by statements from the respondents. We analyzed the literature according to environmental, economic, demographic, social, and political drivers (based on Black et al. 2011a), as well as in terms of food security, which has been described as a driver of migration in arid regions (Neumann and Hermans 2017). The drivers of migration were divided into push and pull factors to retrieve information on the characteristics of destination areas or areas of origin and to address the question regarding which factors are perceived to make a region attractive and which are considered repulsive. The respective factors are shown in Figure 3. For the exact wording of the factors, we refer to Appendix 3 (Table A3.1 and Table A3.2).

A classification of the factors to the drivers is complex because certain factors can be associated with several drivers. However, for our analysis or the visualization of the results, one driver had to be selected. Currently, no standard classification of factors is reported in the literature, thus a classification based on the relevant references was designed in this study. The assignment of environmental factors is based on Black et al. (2011a), describing that weather conditions and land productivity are related to the environment. Black et al. (2011a) and Neumann et al. (2015) described employment opportunities as an economic driver. Lack of available land or access to land are assigned to the category of economic drivers, in line with Parrish et al. (2020), whereas "scarcity of land" is also considered a demographic push factor when it is linked to population pressure. The category of social drivers is subdivided into "social conflicts" (Parrish et al. 2020) as a push factor; we refer to Neumann and Hermans (2017) who describe "escape from family problems" and "escape from assault and violence' as social drivers. "Social network" as well as "educational opportunities" are defined as social pull factors as described in Black et al. (2011a). Political push factors are "political conflicts", including ethnic conflicts, (Black et al. 2011a, Neumann et al. 2015) and "poor infrastructure" (Parrish et al. 2020), whereas "better infrastructure" and "safety" are defined as political pull factors. Economic and political drivers are closely interrelated, as Neumann et al. (2015) emphasize. The factor "infrastructure" needs to be disentangled to differentiate economic infrastructure and infrastructure in the context of political aspects. For this reason, we classify "access to market" as an economic driver (Deen-Swarray et al. 2014). In case studies where "infrastructure" refers to the development of infrastructure, roads and transportation, or access to certain facilities, we consider "infrastructure" as a political factor that depends on regional development policies (Czaika and Reinprecht 2020). Food security as a driver of migration is divided into "food insecurity" as a push factor and "food security" as a pull factor (Neumann et al. 2015). Multiple citations of a factor in the same study were only counted once. However, it was not possible to weight the factors, given that in most case studies quantitative information was missing.

For each study, we determined which pull factors and which push factors were mentioned to better understand the meaning and characteristics of the destination areas and areas of origin. With this information, a matrix was created for each focus country, which served as the basis for the Sankey diagram visualization. The Sankey diagram reflects a specific flow by the width of the lines between two connections and is commonly used to analyze energy or material flows (Schmidt 2008). In this study, the number in the boxes on the outgoing flow of the Sankey diagram show how many pull factors are named in the context of the respective push factors (see Fig. 4). The number on the box of the incoming

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Fig. 3. Overview of the assigned push and pull factors. Push factors are illustrated with a solid line, pull factors with a dashed line.

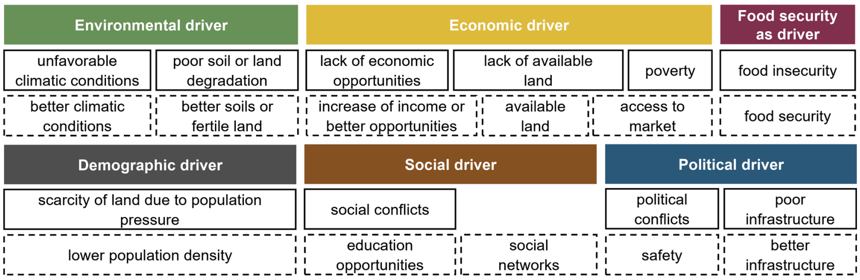
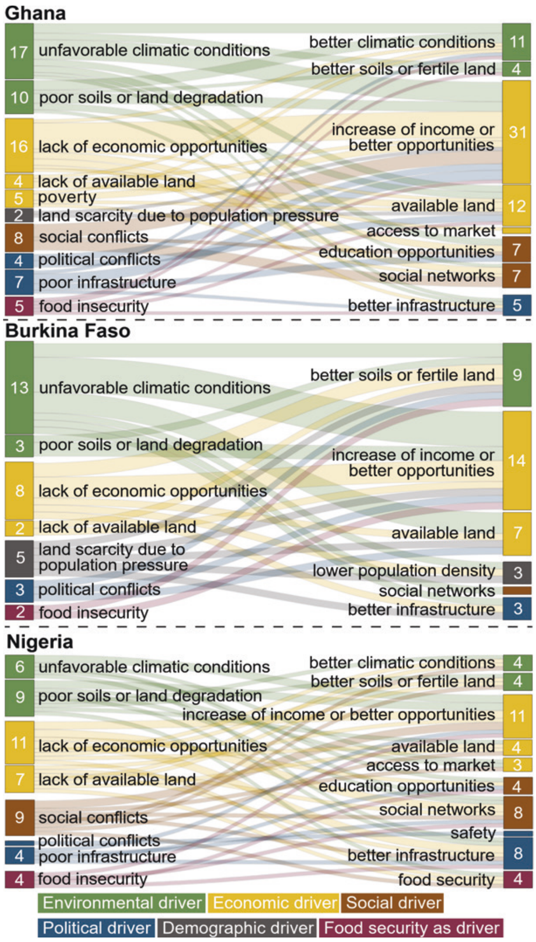


Fig. 4. Sankey diagram showing the interconnections of push and pull factors for Ghana, Burkina Faso and Nigeria. Numbers in the left-sided boxes reflect how many pull factors are named in the context of the respective push factors. Numbers on the right-hand side reflect the number of push factors that are named in the context of the respective pull factors. Colors of the boxes show the same driver categories. Colors of the lines reflect the category of push factors.



flow indicates how many push factors are mentioned in the context of the respective pull factors. The width of lines was determined by how frequently a push factor was cited (counting only once per case study) in combination with a pull factor (multiple counting possible). For a detailed methodological overview of Sankey diagram preprocessing, please refer to Appendix 4 (Fig. A4.1). To generate the diagrams, the Sankey Diagram Generator provided by Acquire Procurement Services was used (http://sankey-diagram-generator.acquireprocure.com/) and subsequently adapted by the authors for better readability.

Migration routes and characterization of destination areas and areas of origin

Migration routes were identified by means of reported destination areas and respective areas of origin. Weighting of the arrows was included in our maps when respective information was provided. Dashed arrows were used for minor migration routes. The reported and categorized push and pull factors of migration were spatially assigned to the mentioned destination and areas of origin (see Fig. 5 and Fig. 6). For the spatial representation, ArcGIS Pro version 2.4.1 was used. Furthermore, infographics in the respective map show the push factors in red circles and pull factors in green circles.

RESULTS

Overview of case studies

As mentioned, all selected studies included in-situ surveys. However, the number of respondents and the type of interview or focus group discussion vary, ranging from 20 respondents (West and Nébié 2019) to 8834 (Hampshire 2002). In six studies, the questions focused directly on climate or environmental issues. The remaining studies asked about land use practices or reasons for migration in general, among other topics. In all studies, the migration movement had already taken place. Although most studies related to Burkina Faso link reported migration movements to the main migration waves associated with the droughts of the 1970s and 1980s (Ruf et al. 2015, Jahel et al. 2018), migration patterns in Ghana were affiliated with other events or lacked a temporal classification. Migration patterns after the 1990s to 2000s were mentioned for example in Braimoh (2004), whereas migration during the 2010s was reported in Rademacher-Schulz et al. (2014) and in Owusu-Ansah and Addai (2014). Migration patterns in northeastern Nigeria are mostly linked to the presence of the Islamist group Boko Haram starting in 2009 (Kamta et al. 2020). In Olaniyan and Okeke-Uzodike (2015),

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Fig. 5. Migration flows and drivers in Ghana with allocated push and pull factors; author illustration based on literature review. Source of built-up area: CIESIN et al. 2020b. Explanation of codes: push factors (red circles): fi = food insecurity, la = lack of available land, le = lack of economic opportunities, ls = land scarcity, p = poverty, pc = political conflicts, pi = poor infrastructure, ps = poor soil or land degradation, sc = social conflicts, uc = unfavorable climatic conditions; pull factors (green circles): al = available land, am = access to market, bc = better climatic conditions, bi = better infrastructure, bo = increase of income or better opportunities, bs = better soils or fertile land, eo = education opportunities, sn = social network.

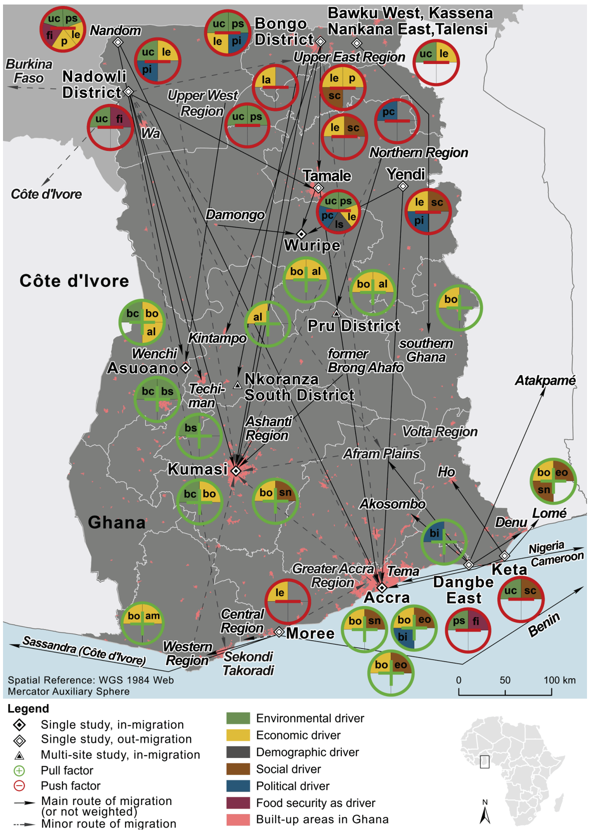
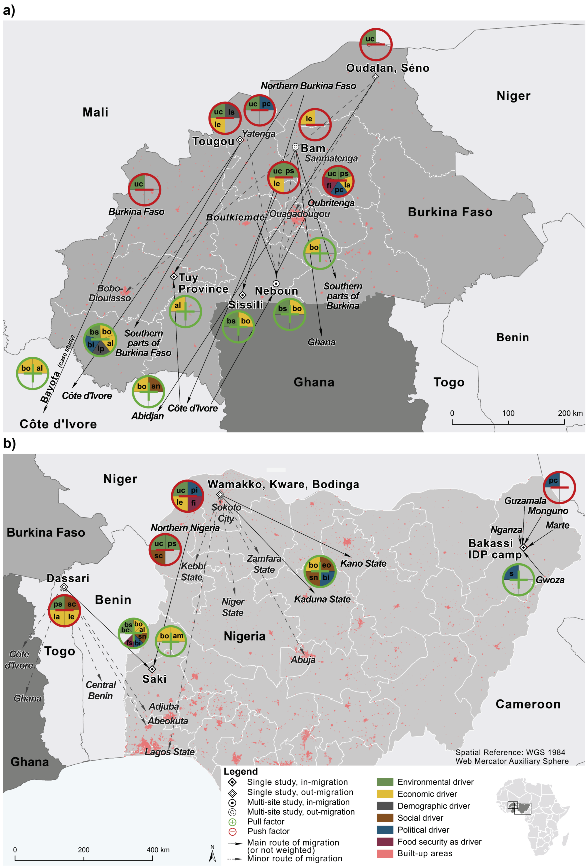


Fig. 6. Migration flows and drivers in (a) Burkina Faso and (b) Nigeria with allocated push and pull factors; author illustration based on literature review. Source of built-up area: CIESIN et al. 2020a, 2020c. Explanation of codes used in the map (sorted alphabetically, categorized by push and pull factors): push factors (red circles): fi = food insecurity, la = lack of available land, le = lack of economic opportunities, ls = land scarcity due to population growth, pi = poor infrastructure, pc = political conflicts, ps = poor soil or land degradation, sc = social conflicts, uc = unfavorable climatic conditions; pull factors (green circle): am = access to market, al = available land, bc = better climatic conditions, bi = better infrastructure, bo = increase in income & better opportunities, bs = better soils, eo = education opportunities, fs = food security, lp = lower population density, s = safety, sn = social network.



migration in Nigeria was described in the context of the 1960s and from 1990 onward. In 12 studies, a quantification of drivers was provided (Dreier and Sow 2015, Goldbach 2017) and in six studies, the number of migrants was specified (Hampshire 2002, Ango et al. 2014). The majority of studies (16) deal with rural to rural migration, although 13 studies address rural to urban migration and one study addresses urban to rural migration. Migration types cited in the case studies are long-term and permanent migration (21), seasonal migration (seven), short-term migration (four), and temporary migration (one). More than half of the selected case studies (17) focused only on internal migration (Ouedraogo et al. 2009, van der Geest 2011, Sward 2017). Fulani and Mossi as migrants were the most frequently cited ethnic groups (Barbier et al. 2009, Olaniyan and Okeke-Uzodike 2015, West and Nébié 2019).

Frequency of push and pull factors

A first overview indicated that economic drivers featured in 22 studies, environmental drivers in 18 studies, political drivers in 12

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studies, social drivers in nine studies, food security as a driver in six studies, and demographic drivers in two studies. In total, 10 sub-categories for push factors and eleven sub-categories for pull factors were defined. Figure A5.1 in Appendix 5 shows the summarized push and pull factors by number of case studies, categorized by drivers of migration and by country. Overall, we identified 124 individual factors, of which 66 are counted as push factors and 58 as pull factors (see Appendix 3, Table A3.1 and Table A3.2). The majority of the push factors are associated with the environmental category (25). In contrast, the pull factors are mainly of economic character (30). Most factors are identified for Ghana (38 push and 29 pull factors), whereas for Burkina Faso (16 push and 15 pull factors) and Nigeria (12 push and 13 pull factors), fewer factors were specified, reflecting the smaller number of studies.

Interconnection of drivers

In 19 studies, a combination of at least two push factors was counted, with the same number applying to pull factors. The interrelation between push and pull factors becomes visible in the Sankey diagrams provided for each focus country (Fig. 4).

In Ghana, economic pull factors were found to play the most important role, as each push factor was reported in combination with an economic pull factor. The second most frequently cited pull factor “available land” was named in combination with push factors from all driver categories. “Better climatic conditions” is mostly cited together with environmental or economic pull factors. It is notable that each pull factor was named together with push factors from multiple driver categories. This observation also applies to the majority of pull factors in the other focus countries.

As in Ghana, the most frequently cited push factors in Burkina Faso include environmental drivers, but economic drivers are dominant for pull factors. Although “food insecurity” occurs together with “better soils or fertile land” or “increase of income or better opportunities,” food security was not reported as a pull factor in Burkina Faso. Moreover, the pull factors “access to market” and “better climatic conditions” were not quoted. “Available land” and “better soils or fertile land” were cited alongside “unfavorable climatic conditions” and “land scarcity due to population pressure.”

Although Nigeria was only represented in four cases, a similar trend can be observed. In fact, environmental and economic push and pull factors seem to be the most important factors here as well. The most frequently reported push factor, as in the other focus countries, is “lack of economic opportunities.” The pull factor “safety” was only cited in the context of Nigeria, alongside the push factor “political conflicts.”

Migration flows identified in studies

Given that the selected case studies report on areas of destination and origin, we were able to depict migration paths, directions and allocate the respective push and pull factors, as illustrated in Figures 5 and 6 for Ghana, Burkina Faso, and Nigeria. In northern Ghana, areas of out-migration were situated in the Upper West Region (Nadowli District and Nandom), in the Upper East Region (Bongo District as well as Bawku West, Kassena Nankana East, and Talensi) and the Northern Region (Tamale, Yendi), where unfavorable climatic conditions like insufficient rainfall or droughts as well as poor soil fertility, food insecurity, and the lack of employment opportunities were named as push factors (van der Geest 2011, Rademacher-Schulz et al. 2014, Adamtey et al. 2015, Tufuor and Sato 2017, Aniah et al. 2019, Antwi-Agyei and Nyantakyi-Frimpong 2021). Migrants from these regions mainly migrate to southern parts of Ghana such as Kumasi, Techiman, or Accra in order to find work or more fertile land.

Out-migration from the Greater Accra Region (Dangbe East), Volta Region (Keta), and Central Region (Moree) occurred for multiple reasons such as poor economic situations, the destruction of landing sites for canoes, or the impact of storms (Marquette et al. 2002, Codjoe et al. 2017, Goldbach 2017). In the respective destination areas, migrants wanted to find better educational opportunities, better markets, or safe landing sites (Marquette et al. 2002, Codjoe et al. 2017, Goldbach 2017). In-migration took place in Savannah Region (Wuripe), Bono Region (Asuoano), Bono East Region (Pru District, Nkoranza South Municipal District), Ashanti Region (Kumasi), and Accra. These regions attracted individuals primarily on account of improved economic conditions and access to farmland (Adjei-Nsiah et al. 2004, Braimoh 2004, Owusu-Ansah and Addai 2014, Sward 2017). Migrants left their home regions, located particularly in the northern regions of Ghana, because of scarcity of land, erratic precipitation, or the desire to find better jobs (Adjei-Nsiah et al. 2004, Braimoh 2004, Owusu-Ansah and Addai 2014, Sward 2017).

The literature review identified three case studies in northern Burkina Faso (namely in the districts Nord, Centre-Nord, and Sahel), where out-migration occurred (Fig. 6a; Hampshire 2002, Barbier et al. 2009, West and Nébié 2019). People migrated from these regions to southern Burkina Faso, to Ghana, or to Côte d’Ivore. Environmental factors like frequent droughts, saturation of land, or lack of drinking water for animals, as well as economic factors such as limited off-farm income opportunities, were the main reasons for migration (Hampshire 2002, Barbier et al. 2009, West and Nébié 2019). Three case studies involved in-migration to locations in Burkina Faso (Ouedraogo et al. 2009, Jahel et al. 2018, West and Nébié 2019) in the districts Centre-Ouest (Neboun and Sissili) and Hauts-Bassins (Tuy Province). Fertile lands or the opportunity to make a better income were pull factors (Ouedraogo et al. 2009, Jahel et al. 2018, West and Nébié 2019). In-migration from Burkina Faso to Bayota in Côte d’Ivoire was reported in Ruf et al. (2015). According to this study, migrants were looking for land for cocoa plantations and better future opportunities given that they were affected by climate change in their areas of origin.

Out-migration in Nigeria took place in Sokoto State (Fig. 6b), from which migrants temporarily moved to Kano State or Kaduna State in search of better economic opportunities and educational facilities (Ango et al. 2014). Migrants left Sokoto State, especially the Local Government Areas Wamakko, Kware, and Bodinga, because of lack of social facilities and poor employment opportunities. In Benin (Dreier and Sow 2015), out-migration to the cities Saki, Adjuba, and Abeokuta (Oyo and Ogun State) in Nigeria was reported. The main reasons for migration were limited land and food insecurity (Dreier and Sow 2015). Migrants from Benin, who stay for a short or for a long

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time, stated they came for better access to land and to find better soil quality in the mentioned locations. Because of the Islamist group Boko Haram and the resulting conflicts, people in northeastern Nigeria had to move to the Bakassi internally displaced people's (IDP) camp in Maiduguri, where they sought refuge (Kamta et al. 2020). In-migration was reported in a case study in Saki (Olaniyan and Okeke-Uzodike 2015), where migrants came from northern Nigeria because of erratic rainfall or decreasing grazing opportunities. They stated they moved to Saki because of climate-related and economic issues.

DISCUSSION

Interrelation of push and pull factors

When the reported reasons for migration are depicted in Sankey diagrams, it becomes apparent that the presence of factors that attract people to an area do not imply that these factors are absent on the sending side. Thus, our findings indicate that the counterpart of a pull factor is not necessarily identified as the push factor. For example, the push factor "unfavorable climatic conditions" is not inevitably accompanied by "favorable climatic conditions" as a pull factor. In this regard, it becomes clear that there is an interplay of different drivers of migration. This is highlighted in the overview maps as a result of the categorization and symbolization of the reasons for migration according to the respective drivers. The review of studies underscores that environmental factors are important in the context of migration in West Africa. Nevertheless, it also emerged that particularly economic, followed by social and political factors, have a significant impact in respect of migration decisions. This observation is in line with van der Land et al. (2018), who conclude that environmental drivers are strongly linked to additional factors, such as the economic or social situation of each individual, but also structural or political conditions. This finding is further supported by the Sankey diagrams which show that the majority of pull factors were cited in combination with push factors of multiple driver categories. Moreover, this result suggests that the decision to migrate depends on the concurrence of multiple unfavorable determinants.

Although unfavorable environmental conditions appear to be a pushing factor in Ghana and Nigeria, economic drivers have an equal importance. With regard to Ghana, better economic conditions and the availability of fertile land in the destination region are more likely to be the reasons for migration than unfavorable climatic conditions for agriculture in the place of origin (van der Geest 2011, van der Land et al. 2018). Given this set of observations, the relationship between environmental and economic drivers appears to be particularly complex within the context of migration research. Another result worth highlighting is the relevance of social factors in Ghana and Nigeria. Family ties in the destination area and the desire for better educational opportunities seem to pull individuals. In other words, individual characteristics of migrants substantially influence migration decisions (van der Land et al. 2018).

It becomes evident that in Burkina Faso environmental factors—especially droughts, erratic rainfall, or declining soil fertility—were frequently mentioned in combination with out-migration. Sanfo et al. (2016) confirmed this observation by arguing that dry spells and droughts are pushing people to migrate. However, the Sankey diagram revealed that these factors are closely related to economic drivers such as available land or increase of income. This assumption was also confirmed by Henry et al. (2004), whose results indicate that individuals in Burkina Faso do not migrate only because of unfavorable climatic conditions. Although environmental conditions are related to migration behavior, they are linked in a rather complex way, also depending on the different types of migration, particularly short- or long-term migration (Henry et al. 2004). In Burkina Faso, it is noticeable that factors connected to population density were mentioned more frequently when compared with the case studies in Ghana and Nigeria, even though the population density per district is comparatively lower. This may be attributed to the relatively high rate of population growth in Burkina Faso, which has been approximately 2.9% since the late 1990s (World Bank 2021). Survey data published by Sanfo et al. (2017) confirm the assumption that population pressure results in land degradation and land tenure insecurity.

Political drivers are related to conflicts in Côte d'Ivoire (Ouedraogo et al. 2009, Jahel et al. 2018), conflicts due to the presence of Boko Haram in northeastern Nigeria (Kamta et al. 2020), or violent conflicts with Fulani herdsmen in Nigeria (Olaniyan and Okeke-Uzodike 2015). However, the latter is not included as a factor of migration in the analysis, as it was not stated as a cause of migration itself, but as a consequence of migration (Lenshie et al. 2020). Meaning, as Olaniyan and Okeke-Uzodike (2015) described, climate change–induced migration of Fulani pastoralists may result in conflicts with the local residents due to economic competition or reluctance to assimilate and identify with local cultural values.

Migration patterns

The case studies analyzed reveal a consistent picture, namely that northern regions of a country connect with its central or southern parts (see Fig. 5 and Fig. 6). This is true for all three focus countries and is also in line with other literature (Henry et al. 2003, Bassett and Turner 2007, Adaawen et al. 2019). Migration patterns are complex (Konseiga 2005), with some places serving as transit stations before migrants move on to their final destination (Owusu-Ansah and Addai 2014, Rademacher-Schulz et al. 2014).

The visual analysis indicates that the most common migration patterns within Ghana are from northern to southern regions, as discussed in several studies (van der Geest et al. 2010, Black et al. 2011c, Adaawen and Owusu 2013, Antwi Bosiakoh et al. 2014), but also between coastal regions of different countries or to the central part of Ghana (Marquette et al. 2002, Codjoe et al. 2017, Goldbach 2017). Figure 5 clearly shows that destination areas, which are predominantly located in the middle belt of Ghana, appear to be characterized primarily by more favorable economic opportunities and higher earnings, as well as better access to land. The capital Accra is a major destination area given its educational and economic opportunities. In contrast, areas of origin are mainly affected by unfavorable climatic conditions or the absence of economic opportunities and are particularly located in the northern Regions.

We identified migration routes both from Côte d'Ivoire to Burkina Faso and vice versa, which is also consistent with current estimations by UNDESA (2019). This migration route corresponds to the largest corridor when looking at migration

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patterns within Africa (UNCTAD 2018, McAuliffe et al. 2019). For internal migration, our study revealed that people in Burkina Faso mainly migrate from north to south, which is also supported by Adaawen et al. (2019) and Henry et al. (2003).

Internal migration movements in Nigeria do not appear to have been explored in depth in the existing literature. Likewise, given the criteria defined in the methods, pertinent literature may not have been part of this analysis, which of course cannot be all-encompassing. The fact that government and academic institutions have focused heavily on international migration in recent years (Oyeniyi 2013) may also explain why we found few case studies related to Nigeria compared to the other focus countries. Furthermore, we only found case studies describing internal and international in-migration or internal out-migration, whereas out-migration to other countries was not addressed.

When looking at the main corridors identified by UNDESA (2019), it is striking that this study did not identify Mali and Niger as destinations for migrants from Burkina Faso and Nigeria, respectively, although these countries are popular destinations. Also noticeable is the fact that migrants are willing to travel long distances. For example, migrants from the villages Séno and Oudalan in Burkina Faso travel a distance of 1200 km to their destination Abidjan in Côte d'Ivoire (Hampshire 2002). Likewise, migrants from Tougou or other regions in northern Burkina Faso travel long distances to Côte d'Ivoire (Barbier et al. 2009). In Ghana, this applies to migrants from Nandom, who migrate to Accra, a distance of about 800 km (Antwi Bosiakoh et al. 2014). This observation could indicate that migration is mainly performed by individuals who possess certain financial resources to travel these distances.

The identified studies of individuals either out-migrating because of lack of access to land or in-migrating for available land (Braimoh 2004, Barbier et al. 2009, Ouedraogo et al. 2009, Dreier and Sow 2015, Ruf et al. 2015, Sward 2017, Jahel et al. 2018) may contribute to more targeted use of land registration tools to strengthen land rights. Secure land rights are major development goals addressed in SDG 1 (no poverty), SDG 2 (zero hunger), SDG 5 (gender equality), SDG 11 (sustainable cities and communities), and SDG 15 (life on land), all of which directly affect migration issues (see the Land Portal SDG land tracker, https://landportal.org/book/sdgs). Our study could support the documentation and monitoring of the SDGs. In addition, the migration-related data obtained in this study, such as migration status, ethnicity, or geographic location, may support the fulfillment of SDG 17.18 (capacity-building for reliable data availability).

Methodological discussion

In our study, we were able to create an overview of reasons for migration and migration routes in West Africa analyzing studies from interdisciplinary social, economic, and natural sciences. We developed new approaches of visualization, tested new combinations of analysis and generated a new classification of migration. Destination areas and areas of origin can now be studied in a more targeted manner, and the individual indicators of migration defined in this literature review can be analyzed in more detail as they are already spatially allocated. Although similar trends of reasons for migration are evident in the three focus countries, the small number of case studies, the partly dated migration patterns, and the restriction to Ghana, Burkina Faso, and Nigeria preclude a generalization of our findings. Although this statement also applies to migration routes, they generally reflect today's migration corridors, despite some of the data relating to past events. However, the reasons why people migrate along these routes may have changed over time.

The classic push–pull model can serve as a starting point for accumulating the reasons for migration and allocating factors to areas of destination and origin even though de Haas (2011), Castelli (2018), and Gemenne and McLeman (2018) perceive this model as too simplistic and deterministic. De Haas (2011) criticized this model for tending to characterize migrants as passive actors driven by macro-level drivers (i.e., environmental conditions or population growth) and not considering migration as a process. As this study only considers case studies in which the local population was interviewed, the individual motives for migration, i.e., the micro-level factors, are part of the analysis and thus represent the push and pull factors as direct perceptions of the respondents. Moreover, we argue that the model is intuitive and easy to visualize, allows the analysis of factors for migration in a structured way, and provides a first overview of causes, patterns, and interrelationships of migration (van Hear et al. 2018).

We agree with van Hear et al. (2018), Castelli (2018), and de Haas (2011) that the drivers have to be considered under different dimensions. Although we assigned the factors to the respective driver categories in accordance with the literature, there is a problem of clear distinctive assignment, especially for the factors "poor infrastructure" and "better infrastructure." We assigned them as political drivers following Czaika and Reinprecht (2020) on account of the higher actuality of reference, but according to Deen-Swarray et al. 2014, assignment as an economic driver is feasible as well. Therefore, we have included a Sankey diagram with these changes in Appendix 6 (Fig. A6.1), which shows a predominance of economic factors. With the spatial assignment of push and pull factors as well as the assignability of ethnic groups, a temporal scale or migration types, multiple dimensions were addressed in our study, even if only superficially. These dimensions, along with others, are proposed by van Hear et al. (2018) as part of their push-pull-plus model, which could not be implemented in our analysis because of a lack of information in some of the case studies. Nevertheless, in this study we extended the classic push–pull model by a visual analysis component and applied it to characterize destination areas and areas of origin. The reasons for migration were not considered in isolation; rather, the interplay of factors influencing the decision to migrate was elaborated using this model.

The Sankey diagrams show at first sight the interaction between the push and pull factors and thus show that the majority of the coupled factors do not belong to the same driver. However, these results depend directly on the research questions and objectives addressed in the individual studies. Given that the studies have a wide spread in the topics of the questionnaires, the results can be assumed to have a low level of bias. A limitation of Sankey diagrams could be the number of linkages to ensure traceability. Moreover, a higher number of connections between push and pull factors may not reflect that one factor is more relevant than another, but rather that the literature focuses on a particular group of factors (e.g., environmental factors of migration). Besides, we were unable to disaggregate the data by gender, which would be important to account for all dimensions of migration, because independent female migration patterns have become increasingly important as strategies for coping with poverty and social pressure in recent years (Adepoju 2003, Tufuor and Sato 2017, Lattof et al. 2018, Onyeneke et al. 2019).

For a holistic picture of migration patterns in West Africa, future studies should include francophone literature as well as gray literature (e.g., from the UN or World Bank), which were only considered as background information in this study. Moreover, comparing the occurrence of the factors over time is challenging, as only a few studies clearly document the implementation date of the surveys or the addressed migration movements. Surveys were often conducted with people who migrated at some point in the past. Consequently, our maps do not reflect current migration trends. Nevertheless, the findings allow us to draw conclusions about current migration patterns and serve as a basis for defining migration hot spots in the focus countries. Follow-up research of our analysis could focus on a finer distinction of drivers of individual migration factors (Fig. 3) by assigning a gradual weight to each relevant driver of the respective factor. The approach of ranking and weighting the most relevant drivers per factor could be combined with interviews and surveys with migration experts. Furthermore, by a Delphi approach with experts (Okoli and Pawlowski 2004), the relation between past, present, and future drivers of migration could identify how the circumstances or motives related to migration have changed or might change over time. In addition, documentation of the success of migration and how it has changed livelihoods would be of research interest. This would allow for inferences on how living conditions of individuals affect migration processes. Long-term information on migration patterns can thus contribute to the achievement of specific SDGs that address poverty alleviation (SDG 1), improved health and well-being (SDG 3), or combating and adapting to the impacts of climate change (SDG 13).

CONCLUSION

The purpose of this paper was to review and analyze survey-based case studies and migration routes, as well as the factors that drive migration, and to visualize their interplay. The evaluation of 26 case studies confirmed that environmental and economic drivers were the main forces affecting migration in the focus countries Ghana, Burkina Faso, and Nigeria. Although environmental factors were among the most frequently cited reasons for out-migration, economic factors appeared to be the most powerful factor attracting people to particular regions. Our visual analysis demonstrates that push and pull factors of the relevant drivers are closely interrelated, but that the counterpart of a push factor is not necessarily identified as the pull factor. The compilation of available information underlines the assumption that the decision to migrate depends on the coincidence of several unfavorable factors, based on the fact that in about 75% of the cases more than one push factor was mentioned. By means of the push–pull model, it was possible to spatially allocate and characterize destination areas and areas of origin with factors influencing migration and to illustrate these results in overview maps. In addition, Sankey diagrams appeared to be a useful tool to emphasize the outcomes of the overview maps, in particular with regard to disproving the assumption that a destination area is characterized by the very factors that are not present in the area of origin. This approach resulted in a novel enhancement of the classical push–pull model that can be easily adapted to other study areas. By identifying factors that motivate people to migrate and allocate them to locations where out- or in-migration took place, policy and decision makers can use these insights for the compliance and achievement of certain SDGs or the targeted registration of land.

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/13489

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Data Availability:

All data used to create figures and tables are from the reviewed articles which can be found in Appendix 1 (Table A1.1). Thus, the data used in this manuscript is freely accessible to everybody referring to the published articles.

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Appendix 1

Table A1.1 *Studies included in the systematic literature review.*

Country	Study	Method	Main focus of interviews	Area of origin	Destination area	Migration data based on the year	Ethnic group of migrants	Migration type
Ghana	Adamtey et al. 2015	Survey (699 respondents)	reasons for migration, socio-economic well being	Yendi Municipality	Agbogbloshie (Accra)	not specified	Dagomba, Konkomba	rural to urban, internal, long-term
	Adjei-Nsiah et al. 2004	Survey (40 & 38 respondents), focus group discussion	soil fertility and land tenure issues	Upper West Region	Asuoano	not specified	Lobis, Walas and Dagabas	rural to rural, internal, permanent, annual
	Aniah et al. 2019	Survey (150 respondents), focus group discussion, key informant interviews	adaptation strategies to climate variability	Bongo District (Gowrie Kunkua and Soe Kabre)	southern Ghana (Tamale, Kumasi, Accra Kintampo)	not specified	not specified	rural to rural, rural to urban, internal, seasonal
	Antwi-Agyei and Nyantakyi-Frimpong 2021	Survey (555 respondents), stakeholder workshops, focus group discussion	socio-demographic characteristics, perceptions of climate change, access to climate information services, coping practices,	Bawku West District, Kassena Nankana Municipal, Talensi District	southern Ghana	not specified	not specified	rural to rural, rural to urban, internal, seasonal, long-term
	Antwi Bosiakoh et al. 2014	Survey (96 respondents)	migration perception and predisposition, migration impacts	Nandom	Accra	not specified	not specified	rural to urban, internal, seasonal, long-term
	Braimoh 2004	Survey (35 respondents), land use change analysis	socio-demographic characteristics, reasons for migration, farming technology, farm size	Tamale, Damongo, Yendi	Wuripe	1989 - 2001	not specified	rural to rural, urban to rural, internal, seasonal

Table A1.1 (continued)

Country	Study	Method	Main focus of interviews	Area of origin	Destination area	Migration data based on the year	Ethnic group of migrants	Migration type
	Codjoe et al. 2017	Survey (350 respondents), focus group discussion	socio-demographic characteristics, experience of sea flooding in the household, migration status	Dangbe East District (Anyakpor, Ocanseykope, Ada-Foah)	Tema, Denu, Akosombo, Afram Plains, Atakpamé, international: Togo, Nigeria, Cameroon	not specified	not specified	rural to urban, internal, international, long-term
	Goldbach 2017	Survey (190 respondents)	socio-demographic characteristics, reasons for migration, migration intentions	Keta	Accra, Ho, Lomé	not specified	not specified	rural to urban, internal, international, long-term
	Marquette et al. 2002	Survey (120 respondents), focus group discussion	socio-demographic characteristics, fishing activity, fishery-related migration	Moree	Western Region, Central Region, Côte d'Ivore (Sassandra), Benin	1990s	Fante	rural to rural, internal, international, seasonal, long-term, short-term
	Owusu-Ansah and Addai 2014	Survey (100 respondents)	socio-demographic characteristics, place of origin, motives for migration, length of stay	Regions: Upper East, Ashanti, Brong Ahafo, Upper West, Greater Accra, Western, Volta, Northern	Kumasi	2004-2014	Frafra and others	rural to urban, internal, long-term, short-term (transit)
	Rademacher-Schulz et al. 2014	Survey (158 respondents), participatory rural approaches, expert interviews	perception of rainfall variability, coping strategy to food insecurity	Nadowli District (Zupiri, Takpo, Mantari and Nanville)	Kumasi, Techiman, Tamale, Accra, Sekondi Takoradi, Afram Plains, Bolgatanga, Wa, Côte d'Ivore, Burkina Faso	2011	not specified	rural to rural, rural to urban, internal, international seasonal

Table A1.1 (continued)

Country	Study	Method	Main focus of interviews	Area of origin	Destination area	Migration data based on the year	Ethnic group of migrants	Migration type
	Sward 2017a	Survey (60 respondents)	tenure norms and land use practices	Northern Region	Pru District	not specified	Gonja, Konkomba, Dagomba, Mamprusi, Chokossi	rural to rural, internal, long-term
	Sward 2017b	Survey (27 respondents), focus group discussion	tenure norms and land use practices	Upper East Region	Nkoranza South	after 1983 (- 2014)	Grusi, Frafra, Kusasi, Dagaba	rural to rural, internal, long-term
	Tufuor & Sato 2017	Survey (230 respondents), focus group discussion	circumstances of migrant women, motivations for migration	Tamale Metropolitan District, Savelugu-Nanton District, Tolon-Kumbungu District	Accra	not specified	Dagomba	rural to urban, internal, short-term, long-term
	van der Geest 2011	Survey (203 respondents)	reasons for migration	Nandom	Wenchi	2000	Dagara	rural to rural, internal, long-term
Burkina Faso	Barbier et al. 2009	Survey (205 respondents), focus group discussion	farmers' perceptions of climate variability and its impact	Tougou	southern part of Burkina Faso and Côte d'Ivoire	2004 / 2006, after the drought and 1970s/80s after the drought	Fulani and Mossi	rural to rural, internal, international, permanent
	Hampshire 2002	Survey (8834 respondents)	types of migration, migration motivation	Oudalan and Séno	Abidjan (Côte d'Ivore), Ouagadougou, Bobo-Dioulasso	1994-1995	Fulani (and subgroups e.g. FulBe DjelgoBe, RiimaaiBe)	rural to urban, internal, international, seasonal

Table A1.1 (continued)

Country	Study	Method	Main focus of interviews	Area of origin	Destination area	Migration data based on the year	Ethnic group of migrants	Migration type
	Jahel et al. 2018	Survey (50 respondents), land use change analysis, population projections	development of farming and expansion strategy, annual development of the plot structure	Northern Burkina Faso, Côte d'Ivoire	Tuy Province	1970s and 80s (from Mossi Plateau), 2002-2010 from Côte d'Ivore	not specified	rural to rural, internal, international, permanent
	West and Nébié 2019a	Survey (20 respondents), land use change analysis	land-use/land-cover change (LULCC) trends, changes in rainfall, land tenure, land-use practices, and migration	Bam	Côte d'Ivoire, Ghana, southern regions of Burkina Faso	main out-migration wave between 1975 -1996	Mossi	rural to rural, internal, international, long-term
	West and Nébié 2019b	Survey (20 respondents), land use change analysis	LULCC trends, changes in rainfall, land tenure, land-use practices, and migration	Northern parts of Burkina Faso	Sissili	main out-migration wave between 1975 -1996	Mossi, FulBe	rural to rural, internal, long-term
	Ouedraogo et al. 2009	Survey (175 respondents), land use change analysis	income generating activities from forest exploitation or agriculture, reasons for migration	Boulkiemdé, Oubritenga, Yatenga, Sanmatenga, Bam	Neboun	1976 - 2007	Mossi, Fulani	rural to rural, internal, long-term
	Ruf et al. 2015	Survey (60 respondents)	migration patterns and motivations, cocoa planting	Burkina Faso	Bayota (Côte d'Ivore)	starting in 1970s	not specified	rural to rural, international, long-term

Table A1.1 (continued)

Country	Study	Method	Main focus of interviews	Area of origin	Destination area	Migration data based on the year	Ethnic group of migrants	Migration type
Nigeria	Ango et al. 2014	Survey (120 respondents)	socio-economic factors, reasons for migration, type of business engaged in, perceived income	Sokoto State (Wamakko, Kware, Bodinga)	Kaduna State, Kano State, Zamfara State, Niger State, Lagos State, Sokoto City, Abuja, Kebbi State	not specified	not specified	rural to urban, internal, temporary, permanent
	Dreier and Sow 2015	Survey (36 respondents), expert interviews	livelihood, their perception of climate and environmental change and personal migration experience	Northwest Benin (Dassari)	Nigeria (Saki, Abeokuta, Adjuba), Ghana, Central Benin, Côte d'Ivore	2013	Biabala	rural to rural, internal, international, long-term, short-term
	Kamta et al. 2020	Survey (204 respondents), expert interviews	time people spent in conflict, gender, occupation, income, land ownership, access to water, previous water scarcity, previous migration	Guzamala, Gwoza, Marte, Monguno, Nganzei	Bakassi IDP Camp in Maiduguri	starting 2009	not specified	rural to urban (refugee camp), internal, type of migration is not clear
	Olaniyan and Okeke-Uzodike 2015	Survey (48 respondents)	relationship with the local host communities; and the causes of conflict; perceived consequences of the Fulani grazers' arrival in Saki	Northern Nigeria	Saki	1960s, 1990s onward	Fulani	rural to urban, internal, long-term

Appendix 2

Table A2.1 *References found in 'Web of Science' using the terms listed in Fig. 2. prior to applying criteria for the selection of case studies. References highlighted in gray are cited in the manuscript as supporting literature.*

Reference (first author, year of publication)	**Title**	**DOI**
Abu et al. 2014	Climate change and internal migration intentions in the forest-savannah transition zone of Ghana	https://doi.org/10.1007/s11111-013-0191-y
Adger et al. 2021	Perceived environmental risks and insecurity reduce future migration intentions in hazardous migration source areas	https://doi.org/10.1016/j.oneear.2020.12.009
Amare et al. 2021	Youth Migration Decisions in Sub-Saharan Africa: Satellite-Based Empirical Evidence from Nigeria	https://doi.org/10.1111/padr.12383
Antwi-Agyei et al. 2018	Adaptation opportunities and maladaptive outcomes in climate vulnerability hotspots of northern Ghana	https://doi.org/10.1016/j.crm.2017.11.003
Bassett & Turner 2007	Sudden Shift or Migratory Drift? FulBe Herd Movements to the Sudano-Guinean Region of West Africa	https://doi.org/10.1007/s10745-006-9067-4
Bukari et al. 2020	Diversity and Multiple Drivers of Pastoral Fulani Migration to Ghana	https://doi.org/10.3197/np.2020.240102
Cattaneo & Massetti 2019	Does harmful climate increase or decrease migration? Evidence from rural households in Nigeria	https://doi.org/10.1142/S2010007819500131
De Longueville et al. 2020	Comparing climate change perceptions and meteorological data in rural West Africa to improve the understanding of household decisions to migrate	https://doi.org/10.1007/s10584-020-02704-7
Guodaar et al. 2017	Using a mixed-method approach to explore the spatiality of adaptation practices of tomato farmers to climate variability in the Offinso North District, Ghana	https://doi.org/10.1080/23311886.2016.1273747
Gyimah 2006	Migration and Fertility Behavior in Sub-Saharan Africa: The Case of Ghana	not applicable
Henry et al. 2004	The Impact of Rainfall on the First Out-Migration: A Multilevel Event-History Analysis in Burkina Faso	https://doi.org/10.1023/B:POEN.0000036928.17696.e8

Table A2.1 *(continued)*

Reference (first author, year of publication)	**Title**	**DOI**
Ibrahim et al. 2021	Rural Migration and Relative Deprivation in Agro-Pastoral Communities Under the Threat of Cattle Rustling in Nigeria	https://doi.org/10.1177/2158244020988856
Igwe 2020	Climate Variation-Induced Migration, Land Conflicts, and Security Situation in Nigeria	https://doi.org/10.17561/tahrj.v14.5478
Kumasi et al. 2019	Small-holder farmers' climate change adaptation practices in the Upper East Region of Ghana	https://doi.org/10.1007/s10668-017-0062-2
Kwankye et al. 2009	Independent North-South Child Migration in Ghana: The Decision Making Process	not applicable
Laube et al. 2011	Smallholder adaptation to climate change: dynamics and limits in Northern Ghana	https://doi.org/10.1007/s10584-011-0199-1
Mikal et al. 2020	Domestic migration and mobile phones: A qualitative case study focused on recent migrants to Ouagadougou, Burkina Faso	https://doi.org/10.1371/journal.pone.0236248
Mukhtar et al. 2018	Boko Haram and the Geopolitics of Forced Migration in Nigeria	https://doi.org/10.32890/jis2018.14.4
Ofuoku et al. 2021	Impact of COVID-19-induced rural-rural migration on agricultural productivity in Delta State, Nigeria	http://dx.doi.org/10.17268/sci.agropecu.2021.006
Sanfo et al. 2016	Survey data on key climate and environmental drivers of farmers' migration in Burkina Faso, West Africa	https://doi.org/10.1016/j.dib.2016.11.001
Sanfo et al. 2017	Climate- and Environment-Induced Intervillage Migration in Southwestern Burkina Faso, West Africa	https://doi.org/10.1175/WCAS-D-16-0065.1
Warner et al. 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	https://doi.org/10.1080/17565529.2013.835707
Yendaw 2021	Cross-Border Migration of Itinerant Immigrant Retailers in Ghana	https://doi.org/10.1007/s12134-021-00839-9

Appendix 3

***Table A3.1** Original wording of push factors given in respective studies; G = Ghana, BF = Burkina Faso, N = Nigeria.*

			factor	factor named in study	categorization based on
Environmental driver	unfavorable climatic conditions	G	unfavourable climatic […] resources	Adjei-Nsiah et al. 2004	Black et al. 2011
			recurrent droughts	Aniah et al. 2019	
			inadequate rainfall	Antwi-Agyei et al. 2021	
			harsh weather	Antwi Bosiakoh et al. 2014	
			irregular / unreliable rainfall	Braimoh 2004	
			storms	Goldbach 2017	
			high inter-annual rainfall variability	Rademacher-Schulz et al. 2014	
			poor rainfall pattern	van der Geest 2011	
		BF	drought	Barbier et al. 2009	
			[…] during the dry season, […], when rain-fed agriculture is not possible in the Sahel	Hampshire 2002	
			drought period, climatic risks	Jahel et al. 2018	
			frequent droughts	West and Nébié 2019a	
			erratic rainfall	Ouedraogo et al. 2009	
			climate change and variability	Ruf et al. 2015	
		N	change of environment	Ango et al. 2014	
			worsening weather condition; erratic rainfall	Olaniyan and Okeke-Uzodike 2015	
	poor soil & land degradation	G	unfavourable [..] soil resources	Adjei-Nsiah et al. 2004	Neumann et al. 2015
			inherent poor soil fertility	Aniah et al. 2019	
			declining soil fertility	Braimoh 2004	
			destruction of landing sites for fishing boats as a result of inundation and high cliffs	Codjoe et al. 2017	
			land infertility	van der Geest 2011	
		BF	saturation of land, land degradation	West and Nébié 2019a	Black et al. 2011
			declining soil fertility	Ouedraogo et al. 2009	Neumann et al. 2015
		N	dwindling grazing opportunity	Olaniyan and Okeke-Uzodike 2015	Black et al. 2011
			poor soil conditions	Dreier and Sow 2015	Neumann et al. 2015
Economic driver	lack of economic opportunities	G	lack of jobs	Adamtey et al. 2015	Black et al. 2011, Neumann et al. 2015
			lack of jobs	Aniah et al. 2019	
			lack of employment opportunities	Antwi-Agyei et al. 2021	
			economic deprivation	Antwi Bosiakoh et al. 2014	
			changed employment to farming	Braimoh 2004	
			adverse economic conditions	Marquette et al. 2002	
			seeking jobs	Owusu-Ansah and Addai 2014	
			lack of local means to generate personal income	Tufuor & Sato 2017	

Table A3.1 (continued)

			factor	factor named in study	categorization based on
		BF	lack of opportunities	Barbier et al. 2009	Black et al. 2011, Neumann et al. 2015
			fewer off-farm income opportunities	West and Nébié 2019a	
			lack of economic opportunities	West and Nébié 2019b	
		N	lack of job opportunities	Ango et al. 2014	
			lack and costs of agricultural tools	Dreier and Sow 2015	
	poverty	G	poverty	Owusu-Ansah and Addai 2014	Authors' decision
			poverty	van der Geest 2011	
	lack of available land	G	scarcity of land	Sward 2017b	Parrish et al. 2020
			land scarcity	van der Geest 2011	
		BF	scarcity of arable land	Ouedraogo et al. 2009	
		N	land in northwest Benin is very limited	Dreier and Sow 2015	
Demogr. driver	scarcity of land due to population pressure	G	scarcity of land at source of migration *(Author's note: due to population pressure)*	Braimoh 2004	Authors' decision
		BF	increasing land scarcity *(Author's note: due to population pressure)*	Barbier et al. 2009	
Social driver	social conflicts	G	escape outmoded cultural practices such as female genital mutilation and forced marriages	Adamtey et al. 2015	Parrish et al. 2020
			problems at home	Goldbach 2017	
			escaping from cultural practices	Owusu-Ansah and Addai 2014	
			divorce; widowhood; avoiding arranged marriage	Tufuor & Sato 2017	Authors' decision
		N	parry sorcery/ conflicts	Dreier and Sow 2015	
			natural inclination to migrate	Olaniyan and Okeke-Uzodike 2015	
Political driver	political conflicts	G	ethnic conflict	Braimoh 2004	Black et al. 2011
			disputes over customary land ownership	Sward 2017a	
		BF	conflicts (Ivory Coast)	Jahel et al. 2018	
			politico-economic unrest in the neighbouring Côte d'Ivoire	Ouedraogo et al. 2009	
		N	conflict	Kamta et al. 2020	
	poor infra-structure	G	lack of education facilities	Adamtey et al. 2015	Czaika and Reinprecht 2020
			low infrastructure development	Aniah et al. 2019	
			poor infrastructure	Antwi Bosiakoh et al. 2014	
		N	lack of social infrastructure/facilities	Ango et al. 2014	
Food insec.	food insecurity	G	dwindling fish harvests	Codjoe et al. 2017	Neumann et al. 2015
			food shortages	Rademacher-Schulz et al. 2014	
			hunger; food scarcity	van der Geest 2011	
		BF	need to produce more food	Ouedraogo et al. 2009	
		N	crop failure and famine	Ango et al. 2014	

Table A3.2 *Original wording of pull factors given in respective studies; G = Ghana, BF = Burkina Faso, N = Nigeria.*

			factor	factor named in study	categorization based on
Environmental driver	better climatic conditions	G	where climatic […] resources are more favourable	Adjei-Nsiah 2004	Black et al. 2011
			reduce the effects of climate and ecological change on their livelihood	Aniah et al. 2019	
			more attractive rainfall pattern	van der Geest 2011	
		N	rain fall	Dreier and Sow 2015	
	better soils or fertile land	G	soil resources are more favourable for food production	Adjei-Nsiah et al. 2004	Neumann et al. 2015
			more fertile lands	Rademacher-Schulz et al. 2014	
		BF	pastures are still available	Barbier et al. 2009	
			fertile valley	West and Nébié 2019b	
			seek for pasture to graze their cattle	Ouedraogo et al. 2009	
		N	soil productivity; good harvest	Dreier and Sow 2015	
Economic driver	increase of income or better opportunities	G	seek employment; look for resources to expand or start up business	Adamtey et al. 2015	Black et al. 2011, Neumann et al. 2015
			to work on farms to earn income and accumulate food	Aniah et al. 2019	
			work to make a living; undertake different menial jobs	Antwi-Agyei et al. 2021	
			desire to be successful, desire to support family, desire to tap opportunities in receiving areas	Antwi Bosiakoh et al. 2014	
			to increase output/make more income	Braimoh 2004	
			work	Goldbach 2017	
			avoid poverty in the off-fishing season; to make lump sum savings; lower costs of living; petrol prices	Marquette et al. 2002	
			job opportunities in the city	Owusu-Ansah and Addai 2014	
			relatively good farming prospects	Sward 2017a	
			better life; economic advancement	Tufuor & Sato 2017	
			making money	van der Geest 2011	
		BF	to Côte d'Ivoire where they mainly work in Cocoa plantations	Barbier et al. 2009	
			offering greater economic opportunities	Hampshire 2002	
			better opportunities	West and Nébié 2019a	
			non-farm income generating opportunities	West and Nébié 2019b	
			need to make income	Ouedraogo et al. 2009	
			pulled by perceived future opportunities […] to improve their livelihoods	Ruf et al. 2015	
		N	search for better employment; look for money through labor; to improve livelihood welfare; to learn trade	Ango et al. 2014	
			find paid work in the agrarian sector; accumulation of money; employment; agricultural work; prosperous economic activity; means for construction; available agricultural tools; commerce; bettering of life situation	Dreier and Sow 2015	
			to engage in crop farming	Olaniyan and Okeke-Uzodike 2015	

Table A3.2 (continued)

			factor	factor named in study	categorization based on
	available land	G	more secure land tenure	Braimoh 2004	Parrish et al. 2020
			availability of farmland	Sward 2017a	
			attaining relatively fertile farmland	Sward 2017b	
			abundance and fertility of land	van der Geest 2011	
		BF	pastures are still available; where land is still available	Barbier et al. 2009	
			available lands	Jahel et al. 2018	
			new cocoa farm; access to forest plot	Ruf et al. 2015	
		N	available soils	Dreier and Sow 2015	
	access to market	G	better exchange rates and markets	Marquette et al. 2002	Neumann et al. 2015
		N	need for market	Olaniyan and Okeke-Uzodike 2015	
Demogr. d.	lower population density	BF	[…] where population density is lower	Barbier et al. 2009	Black et al. 2011
Social driver	social network	G	marriage	Goldbach 2017	Black et al. 2011
			family reunion	Owusu-Ansah and Addai 2014	
			escape from restrictive marriage; more freedom; adventure	Tufuor & Sato 2017	
		BF	kin networks	Hampshire 2002	
		N	join family members in the city	Ango et al. 2014	
			personal development, information, networks, adventure	Dreier and Sow 2015	
	education oppor-tunities	G	access to quality education	Adamtey et al. 2015	
			desire to get good quality education	Antwi Bosiakoh et al. 2014	
			education	Goldbach 2017	
		N	further education	Ango et al. 2014	
Political driver	better infrastructure	G	good quality health care; good roads and transport; telecommunication facilities	Antwi Bosiakoh et al. 2014	Czaika and Reinprecht 2020
			harbor or safe landing place [for canoes]	Codjoe et al. 2017	
		BF	where […] *tse tse* fly is under control	Barbier et al. 2009	Authors' decision
		N	better transportation in the urban areas; better housing in the city	Ango et al. 2014	Czaika and Reinprecht 2020
			relatively low transportation costs	Dreier and Sow 2015	
	safety	N	safety and availability of humanitarian assistance	Kamta et al. 2020	Black et al. 2011, Parrish et al. 2020
Food sec.	food security	N	food security	Dreier and Sow 2015	Neumann et al. 2015

Appendix 4

Fig. A4.1 Methodical overview of generating Sankey diagrams.
a) allocation of pull factors mentioned in the combination with push factors. The light blue box shows how a multiple counting of the pull factors occurs. In this example, within the case study Adjei-Nsiah et al. 2004, ‘better climatic conditions’ and ‘better soils or fertile land’ as pull factors were named together with ‘unfavorable climatic conditions’ as well as with ‘poor soil or land degradation’.
b) Illustration of how the assignment of the pull factors results in the pivot table, which serves as basis for the Sankey diagram.

a) Allocation
Pull factors named in connection with the respective pus

Environmental push factors

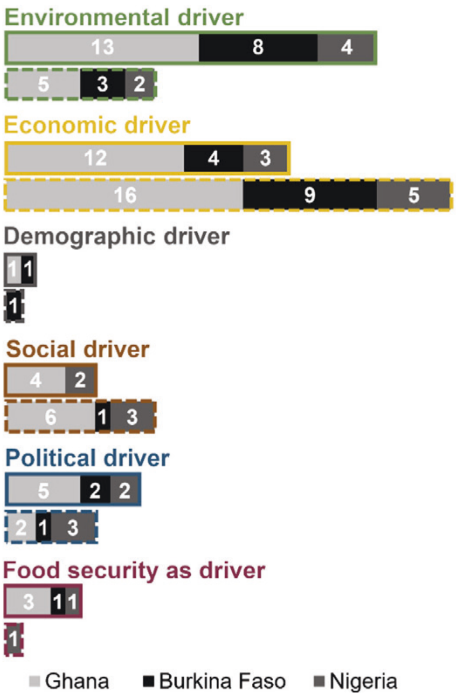
Case Study	push factor	pull factor		
Adjei-Nsiah et al. 2004	unfavorable climatic conditions	better climatic conditions	better soils or fertile land	
Aniah et al. 2019	unfavorable climatic conditions	better climatic conditions	increase of income or better opportunities	
Antwi-Agyei and Nyantakyi-Frimpong 2021	unfavorable climatic conditions	increase of income or better opportunities		
Antwi Bosiakoh et al. 2014	unfavorable climatic conditions	increase of income or better opportunities	education opportunities	better infrastructure
Braimoh 2004	unfavorable climatic conditions	increase of income or better opportunities	available land	
Goldbach 2017	unfavorable climatic conditions	increase of income or better opportunities	social networks	education opportunities
Rademacher-Schulz 2014	unfavorable climatic conditions	better soils or fertile land		
Adjei-Nsiah 2004	poor soil or land degradation	better climatic conditions	better soils or fertile land	
Braimoh, 2004	poor soil or land degradation	increase of income or better opportunities	available land	

b) Matrix
Pivot table as basis for Sankey diagram

push factor	pull factor: better climatic conditions	better soils or fertile land	increase of income or better opportunities	availab lan	access to market	education opportunities	social networks	better infrastructure	food security	sum = number in Sankey diagram
unfavorable climatic conditions	3	2	6	2		2	1	1		17
poor soil or land degradation	3	1	3	2				1		10
lack of economic opportunities	1		8	1	1	2	2	1		16
lack of available land	1		1	2						4
poverty	1		2	1			1			5
land scarcity due to pop. pressure			1	1						2
social conflicts			4			1	3			8
political conflicts			2	2						4
poor infrastructure	1		3			2		1		7
food insecurity	1	1	1	1				1		5
sum = number in Sankey diagram	11	4	31	12	1	7	7	5	0	

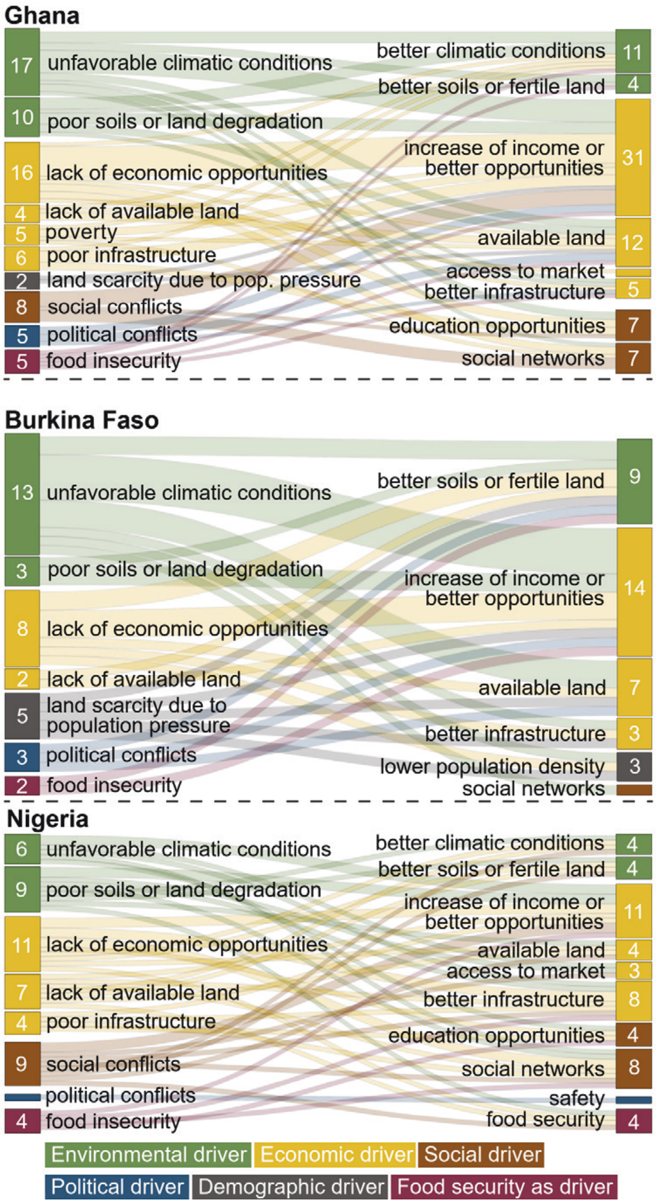
Appendix 5

Fig. A5.1 *Aggregated push and pull factors by number of studies, categorized by drivers of migration and by country. Solid frame indicates push factors, dashed frame indicates pull factors.*



Appendix 6

Fig. A6.1 *Alternative Sankey diagram showing the interconnections of push and pull factors for Ghana, Burkina Faso and Nigeria, with 'infrastructure' being classified as an economic driver.*
Numbers in the left-sided boxes reflect how many pull factors are named in the context of the respective push factors. Numbers on the right- hand side reflect the number of push factors that are named in the context of the respective pull factors. Colors of the boxes show the same driver categories. Colors of the lines reflect the category of push factors



4.2 Mapping socio-environmental vulnerability to assess rural migration in Ghana

Full bibliographic citation:

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Overall aim:

This study aimed to develop a spatially explicit assessment of rural areas in Ghana and identify regions that are vulnerable to socio-economic and environmental factors that could influence migration.

Methodology:

To map vulnerability, a weighted overlay analysis was employed that integrated environmental, socio-economic, and population data, as well as recent net-migration rates. Factors were ranked by local experts.

Key findings:

- High vulnerability and thus higher likelihood of out-migration were observed in the northern and coastal regions of Ghana, while central regions exhibited relatively lower vulnerability.
- Results that are not explainable at first sight might be explained by personal aspirations and perceived opportunities.
- The results are broadly consistent with current net migration rates, confirming the relevance and reliability of the research method for estimating out-migration likelihood.

Relevance to dissertation objectives:

The study highlighted the effectiveness of spatial analysis in identifying vulnerable areas and current rural migration patterns. To address objective 1, the identified factors were ranked based on expert knowledge. This provided a clear picture of which factors influence migration in Ghana the most. This study contributes to objective 2 by overlaying weighted unfavorable factors with population density data. This approach enabled the spatial identification of areas where multiple stressors intersect and population exposure is high, thereby increasing the potential for out-migration. The alignment between the proportion of the affected population residing in vulnerable areas and actual migration rates proved that spatial analysis can be used to map areas with potential rural out-migration, thus addressing objective 3.

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Mapping socio-environmental vulnerability to assess rural migration in Ghana

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ABSTRACT

Rural communities in Ghana, dependent on agriculture and lacking resources and infrastructure, are highly vulnerable to climate and environmental change. Internal migration is often considered as a strategy to mitigate local livelihood constraints. Understanding the challenges of rural communities requires knowledge of local conditions. As only few studies have mapped vulnerable areas in the context of migration in Ghana at a spatially explicit and nationwide level, this study provides a geodata-based examination of how rural areas in Ghana are vulnerable to multiple, co-occurring socio-economic and environmental factors influencing migration. A multifactorial and expert-based weighted overlay analysis was applied, integrating diverse data sources including climate, remote sensing, and recent census data from Ghana. Bivariate maps visualize vulnerable areas where a high impact of the factors coincides with a high rural population density. High levels of factor impact are observed in the northern regions and coastal areas of Ghana. Relatively low impact is found in more central parts of the country. The results align with current net migration rates, confirming the applicability of our method for assessing rural internal migration. This method enhances the understanding of migration dynamics in Ghana and emphasizes the role of spatial data in migration studies.

1. Introduction

Rural communities in Ghana are highly vulnerable to the impacts of climate and environmental changes due to their reliance on agriculture and lack of financial resources, social facilities and infrastructure (Asare-Nuamah, 2021; Baffoe & Matsuda, 2018; Dumenu & Obeng, 2016). Unfavorable environmental conditions like changes in rainfall patterns as well as poor or degrading soil fertility, especially in the savannah zones, are negatively affecting crop yields (Kanton et al., 2016; Owusu et al., 2021). This disruption of agricultural activities (Azumah & Ahmed, 2023; Schraven & Rademacher-Schulz, 2016), the main source of livelihoods for many rural communities (GSS, 2021a), can be exacerbated by increasing rural population densities, leading to scarcity of natural resources and land (Bonye et al., 2021; van der Geest, 2011).

Internal migration is often a strategy to mitigate local livelihood constraints and to diversify income sources. In addition, remittances play a central role to improve the household income (Teye & Nikoi, 2022). In Ghana, individuals or households tend to move from rural to urban areas (Antwi-Agyei et al., 2014; GSS, 2023) in particular from northern to southern regions (Arthur-Holmes & Abrefa Busia, 2022; Teye and Nikoi, 2022) or to less populated rural areas where arable land is still available (Ghana Statistical Service, 2023; van der Geest, 2011). Urban areas like Accra and Kumasi are often perceived to offer greater possibilities due to the lack of employment opportunities and educational facilities in rural areas (Awumbila et al., 2014; Baffoe et al., 2021). At the same time, the high population density in urban areas can intensify competition for jobs and resources (Anarfi et al., 2020; Poku-Boansi et al., 2020). This shows that although migration can bring individual benefits, it can also create potential trade-offs and challenges, as pointed out by Szaboova et al. (2023). The social and environmental vulnerability of urban migrants often extends beyond their place of destination and contribute to their precarious situation (Aboagye, 2021; Szaboova et al., 2022).

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Despite the growing risks posed by climate change, it is rarely cited as the main reason for migration decisions (Abu et al., 2014; Adger et al., 2021; Bukari et al., 2020). In addition, the ways how and the extent to which environmental variability affects migration is an ongoing debate (Kaczan & Orgill-Meyer, 2020). Rapid-onset events often result in (involuntary) displacement (Teye & Nikoi, 2022) whereas gradual climatic processes tend to induce rather internal voluntary migration (Rigaud et al., 2021; Zickgraf, 2021). Individual aspiration, financial resources, and social support are widely recognized as key determinants of human mobility (Flahaux & Haas, 2016; Haas, 2021). These are interrelated with external factors such as environmental degradation, infrastructure development, access to markets or job opportunities as they can shape people's motivation to leave their place of origin (Adger et al., 2024; Black et al., 2011; Czaika & Reinprecht, 2022). Given that individual decisions are too diverse to be captured in sustainable development and planning (Adger et al., 2024), it seems necessary to identify and map migration on the basis of underlying factors. A key question is therefore, whether and how the factors influencing internal rural migration in Ghana can be analyzed and weighted to reflect their impact on migration patterns. Another question is whether this approach is sufficient to understand actual migration movements.

Assessing potential migration requires an analysis of the specific challenges faced by the rural population in the areas of origin. While multiple studies have used spatial data to map the vulnerability of populations to environmental variability in combination with socio-economic factors globally (Carrão et al., 2016; Marzi et al., 2021; Wang & Sun, 2023), for Africa (Busby et al., 2014; Paul et al., 2022) and explicitly for West Africa (Dada et al., 2024; Sherbinin et al., 2015), few have placed this in the context of migration. Spatially explicit research that mapped migration has mainly considered environmental and demographic factors to find hotspots of in- and out-migration (Hermans-Neumann et al., 2017; Neumann et al., 2015; Rigaud et al., 2021) or has analyzed multiple factors on coarser spatial resolution without examining the population in more detail (Mijani et al., 2022). Some previous studies have combined historical district-level net migration rates with environmental or socio-economic data to study migration (Tsegai & Le, 2011; van der Geest, 2011; van der Geest et al., 2010). However, the recent official migration dataset for Ghana (GSS, 2023) has not yet been combined with high-resolution environmental and socio-economic data, nor with spatially explicit population data. Most recent studies have mainly used qualitative methods, such as region-specific surveys (Abu et al., 2014; Antwi-Agyei et al., 2018; Kumasi et al., 2019) or have focused primarily on rainfall data (Issifu et al., 2022; Rademacher-Schulz et al., 2014) to investigate the underlying causes of rural out-migration in Ghana.

There is currently a lack of nationwide and spatially explicit analyses that systematically identifies areas where environmental degradation, unfavorable socio-economic factors, and population pressure overlap. This presents a novel opportunity for further research to address this gap by analyzing multiple expert-weighted environmental and socio-economic factors to map vulnerability and thus assess rural out-migration in Ghana.

The aim of this study is to determine to which extent spatial data can be used to map vulnerable rural areas in Ghana where the likelihood of migration is expected to be high, thereby pinpointing where policies could be implemented to improve rural livelihoods. We use bivariate maps to illustrate the intensity of the examined factors on rural populations in order to locate vulnerable populations, particularly those dependent on agriculture. This mixed-methods approach is situated at the intersection of environmental and social sciences as it involves expert knowledge and enhances the application of spatial data analysis to study human mobility in Ghana. The resulting maps identify geographic regions with specific opportunities that could influence migration decisions and provide a basis for future studies that seek to explore personal motivations for migration. By addressing places of origin, the study enables policy makers to develop more inclusive and effective strategies that respond to the challenges faced by rural households and support the sustainable development of their home areas.

2. Methodology

2.1. Study area

Ghana is located on the Gulf of Guinea and is bordered by Cote d'Ivoire, Burkina Faso, and Togo. It has a land area of 238,533 square kilometers and a population of approx. 31 million people, making it one of the most densely populated countries in West Africa (GSS, 2021b; World Bank, 2020). The population is made up of different ethnic groups such as the Akan (45.7 %), Mole-Dagbani (18.5 %) and Ewe (12.8 %) (GSS, 2021c). The capital city is Accra, and other major cities include Kumasi, Tamale, Sekondi-Takoradi and Tema. Ghana's economy is mainly driven by the agricultural sector, which employs 33 % of the workforce (62.9 % when referred to rural population), followed by the wholesale and retail trade sector (18.7 %), the manufacturing sector (6.7 %) and the education sector (5.9 %) (GSS, 2021a).

The main staple crops grown in Ghana include maize, cassava, yam and plantain (MoFA, 2021). There are significant rural-urban differences in livelihoods and incomes in Ghana. Rural areas, which are predominant in the northern regions of Ghana, are more heavily dependent on agriculture, while urban areas offer a wider range of job opportunities in manufacturing and services (GSS, 2021a). Ghana consists of six agro-ecological zones (Fig. 1), that represent different potentials for agriculture. The zones are characterized by a precipitation gradient that ranges from more semi-arid areas in the north to humid areas in the south, with the coastal savannah being drier than the adjacent zones.

2.2. Methods

The study employs a methodological approach, designed to identify and map vulnerable areas with a high likelihood of migration using spatial data as its core component. Out-migration is defined as the voluntary movement from rural to urban or other rural areas, investigated at the pixel level (100 m cells). Within Ghana, about 8.2 million inhabitants (27 % of the population) are internal migrants (GSS, 2023). The approach is structured into five integral parts, each contributing to its overall functionality and effectiveness (Fig. 2).

1) Literature review: A comprehensive review of the relevant literature was conducted to identify the main factors influencing migration decisions. Upon the findings of previous studies on migration patterns, including the underlying drivers and the impact of various socio-economic, political, and environmental factors (see Black et al., 2011; Neumann et al., 2015; Schürmann et al., 2022), specific factors for expert interviews were identified and used for proxy identification.
2) Expert interviews: The factors identified in the literature review were assessed by interviewing experts of migration research. These experts provided insights into the relevance and importance of the identified factors (see Section 2.2.1).
3) Preprocessing of spatial data: Proxy indicators representing the factors addressed in the expert interviews were identified. This was done by analyzing the available data sources and selecting the most appropriate indicators for each factor. Environmental factors needed extensive preprocessing (see Section 2.2.2).
4) Geographically weighted overlay analysis (WOA): The proxy indicators were included in a WOA. This method enables the factors to be overlaid and weighted according to the perceived importance by the experts. The results of the analysis were then combined with the population density using bivariate maps. This approach facilitated the representation of the vulnerable population and illustrates the

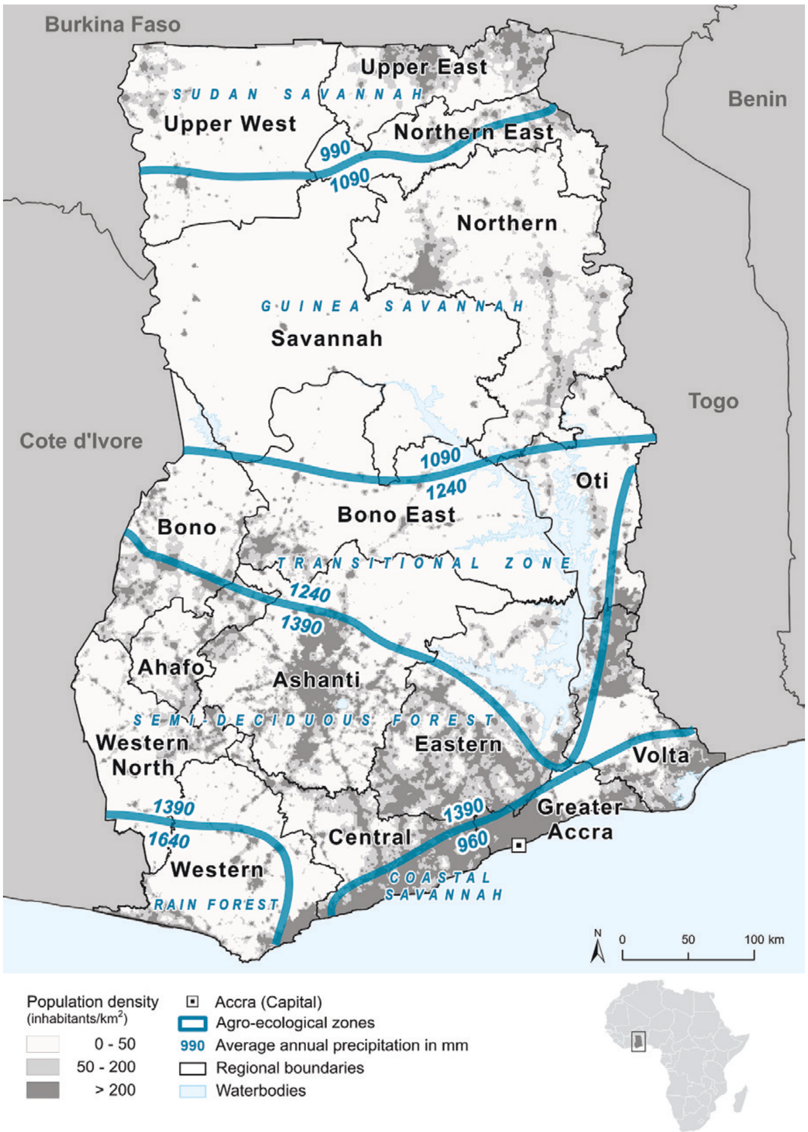

Fig. 1. Ghana with population density (WorldPop & Bondarenko, 2020) and the agro-ecological zones represented by average annual precipitation (in mm) in order to reflect the suitability for farming.

likelihood of migration, considering the adverse factors that influence migration decisions (see Section 2.2.3).

5) Comparative analysis: Current net migration rates from the Ghana Population and Housing Census (PHC) (GSS, 2023), were compared with our results to evaluate the plausibility and to address the applicability of geodata for assessing migration (see Section 2.2.4).

2.2.1. Expert interviews

Fifteen expert interviews (Appendix A) were conducted in Ghana in March and April 2022 to obtain a comprehensive understanding of the key factors that influence migration decisions and to rank the importance of the factors identified. The factors evaluated during the expert interviews are displayed in Table 1. The participants for these interviews were selected from non-/governmental institutions and research institutes that have a focus on human migration or related fields. Each expert had a minimum of three years of experience in migration research. The maximum years of experience were more than 30 years. The interviews were conducted using a questionnaire that combined closed questions related to the impact of individual characteristics on migration decisions, open-ended questions related to migration routes, and Likert scale ratings related to the importance of factors on the migration decision. The latter ones were used for ranking the factors in this study. The questionnaire contained 22 factors, of which 16 were selected for this study given data availability constraints. The Relative Importance Index (RII) was selected to compute a weighting based on the Likert scale, which is calculated as follows:

$$RII = \sum W \Big/ (A*N)$$

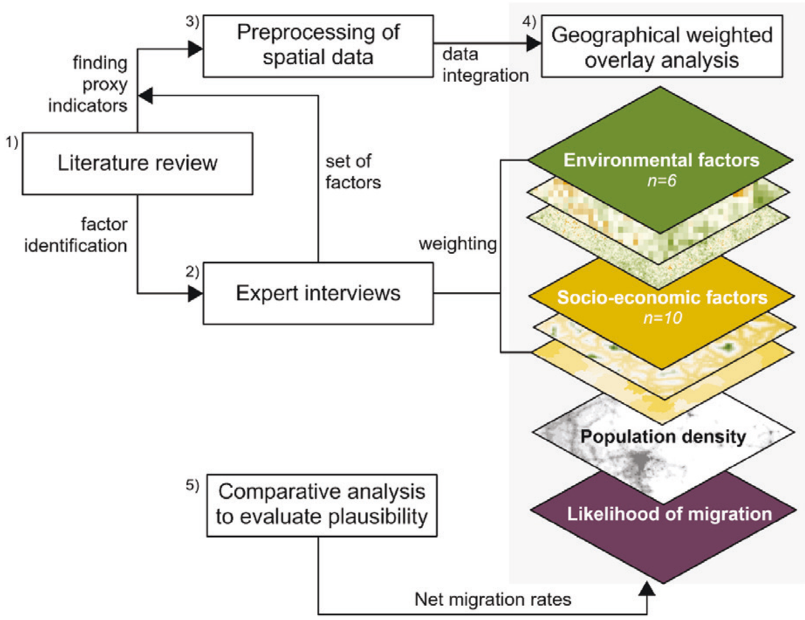

Fig. 2. Analytical approach to address applicability of spatial data to map likelihood of migration, n = number of factors.

Where W is the weighting given to each factor by the experts; ranging from 1 (low importance) to 5 (high importance) for migration in Ghana, A is the highest weight, and N is the total number of respondents. The greater the value of RII, the higher the importance of a factor. For its use in the WOA, the RII has been multiplied by 100. Adjacent to the respective RII, the percentage influence for the WOA and its rounded values are given in Table 1.

2.2.2. Compilation and preprocessing of spatial data

The factors under consideration were categorized into “environmental factors” and “socio-economic factors”. Environmental proxy indicators were available at the pixel level, while most of the socio-economic proxy indicators are based on the PHC data and thus available at the district level. A comprehensive list of the proxy indicators can be found in Table 1.

Long-term environmental degradation in migrants’ areas of origin tends to induce rather voluntary and internal migration (see Section 1). Therefore, the Sen’s slope trend test (Sen, 1968), was utilized to determine the magnitude of the trend for datasets with multiple time steps available using the “trend” package in the R programming language (Pohlert, 2023).

Some proxy indicators required extensive preprocessing, which is explained in the following. Rainfall indices were derived from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Funk et al., 2015). The CHIRPS dataset covers the African continent and spans the period from 1981 to the near present. It combines satellite imagery at 0.05° × 0.05° resolution and in-situ station data to produce gridded precipitation time series suitable for trend analysis and seasonal drought monitoring (Hubertus et al., 2023; Sacré Regis M. et al., 2020). Rainfall indices were computed to explore regional climate effects on agriculture conditions. The onset and cessation dates of the rainy seasons were calculated pixel-wise for each year from 1991 to 2021 using an adapted approach of the method described in Dunning et al. (2016), which extends the methodology of Liebmann et al. (2012). The rainy seasons are determined by calculating the climatological mean rainfall for each day of the year and identifying minima/maxima in the smoothed cumulative daily rainfall anomaly. The onset and cessation of the rainy season correspond to the global minima and maxima of the daily cumulative rainfall anomaly, calculated for 30-day subsets before and after the identified minima and maxima. The accuracy of the method was evaluated by the proportion of precipitation outside the calculated mean rainy seasons (Appendix B). As consecutive rainy days during the rainy season could not be accurately determined in the transition area from the biannual to the annual rainy season, we included the annual number of consecutive dry days in our analysis.

The Normalized Difference Vegetation Index (NDVI) is used to assess vegetation vitality, productivity, and thus an indicator for evaluating land degradation (Mechiche-Alami & Abdi, 2020; Nyamekye et al., 2021). NDVI is a measure of the reflectance in the near-infrared spectrum (wavelength from 0.841 to 0.876 nm) of green vegetation in a specific area. The resulting value ranges from −1 to 1, with higher values indicating higher vegetation vitality. A low NDVI value shows a low level of vital vegetation or no photosynthetic activity. The MODIS products AQUA (MYD13Q1 – Didan, 2021a) and TERRA (MOD13Q1 – Didan, 2021b) were combined, yielding a total of 46 layers per year for the period from 2011 to 2021. Three-month median composites of June, July, and August were created to account for missing pixels due to heavy cloud cover. These months corresponds to the growing season of major food crops (FAO, 2023) and are expected to capture high annual NDVI values. Pixels without information due to cloud cover were eliminated using the pixel reliability layer of the MODIS products. Subsequently, a 5x5 moving window median was applied to fill in missing values in the data. Sen’s slope estimator was used to detect the magnitude of the trend and again, a 5x5 moving window was applied to reduce the number with missing information. Finally, merely only about 2 % of the pixels were classified as “no data” (Appendix B).

For “Agricultural production”, the average yield of the ten major food crops, i.e. maize, millet, rice, sorghum, cassava, plantain, yam, soya bean, groundnut and cowpea (MoFA, 2021), was calculated using the dataset provided by IFPRI (2020). Information on the number of “Armed conflicts” from 2011 to 2021 was obtained from the Armed Conflict Location and Event Data project (ACLED) (Raleigh et al., 2010). The frequency of conflicts with fatilities was then aggregated to the district level. For the indicator “Access to farmland”, the hectares of cropland (based on ESA CCI-LC (Defourny et al., 2023)) per person active in the

Table 1
Factors that were addressed in expert interviews and their proxy indicators. Adm. Level = Administrative level, RII= Relative Importance Index, WOA= Weighted overlay analysis.

	Factors addressed in expert interview	Proxy indicator	Temporal resolution	Spatial resolution/Adm. Level	RII	Source	% of influence in	
							WOA [a]	WOA [b]
Environmental factors	Consecutive dry days in the rainy season	Maximum length of consecutive dry days	1991–2021	5 km	76	Funk et al. (2015)	18	7
	Environmental conditions for agriculture	Later onset of rainy season	1991–2021	5 km	75	Funk et al. (2015)	17	7
	Permanent degradation of land/soils	NDVI in June, July and August	2011–2021	250 m	73	Didan (2021a,b)	17	7
	Fertile soils	Soil organic carbon in 0–20 m	2017	30 m	73	Hengl et al. (2021)	17	7
	Persistent droughts	Annual dry days	1991–2021	5 km	71	Funk et al. (2015)	16	6
	Extreme rainfall events in rainy season	Heavy rainfall events (days with >20 mm) in rainy season	1991–2021	5 km	64	Funk et al. (2015)	15	6
				∑	432		100	
Socio-economic factors	Job opportunities	Unemployment rate in %	2021	district	93	GSS (2021a)	13	8
	Opportunity for trading	Distance to cities (travel time)	2015	2 km	84	Weiss et al. (2018)	12	7
	Agricultural production	Mean yield of ten major food crops	2017	10 km	71	IFPRI (2020)	10	6
	Food security	Prevalence of severe and moderate food insecurity in the population	2020	district	71	MoFA et al. (2020)	10	6
	Poor infrastructure	Nighttime lights in 2021	2021	500 m	68	Elvidge et al. (2017)	10	6
	Access to education	Number of junior high schools per 1000 inhabitants	2021	district	67	GSS (2021d)	10	6
	Access to water	Distance to main source of drinking water	2021	region	65	GSS (2022)	9	6
	Regular armed conflicts	Frequency of armed conflicts with fatalities	2011–2021	district	61	Raleigh et al. (2010)	9	5
	Safety	Number of police stations per 100,000 inhabitants	2021	district	60	GSS (2021d)	9	5
	Access to farmland	Cropland per farmer	2020/2021	district	59	Defourny et al. (2023); GSS (2021a)	8	5
				∑	699		100	100
				∑	1131			
Affected population	Population density (inhabitants/km^2)		2020	1 km		WorldPop and Bondarenko (2020)		
	Population count (number of inhabitants per 100 m cell)		2020	100 m		Schiavina et al. (2023)		

[a] *% of influence in WOA for Impact map 1 and Impact map 2 respectively.*
[b] *% of influence in WOA for Impact map 3.*

agricultural sector (GSS, 2021a) was calculated.

All datasets have been reclassified to create a common scale. This process is illustrated in Fig. 3. As the WOA only allows for raster format, the PHC data was first reclassified into five classes using the natural breaks method (Jenks, 1967), which creates class boundaries that optimize the grouping of similar values while maximizing differences between classes. Subsequently, the PHC data was aggregated to 10 m raster cells using the "Polygon to Raster" tool in ESRI ArcGIS Pro 2.9. The "Raster Calculator" tool in ArcGIS Pro was used to create a new indicator for proxy indicators with available trend estimates. The process involved combining the trend and respective mean layers, which were reclassified into three classes (Appendix C) and then summed, resulting in the creation of five new classes (Fig. 3). This approach considers areas where the factor is already unfavorable on average and has deteriorated over the last years. Other proxy indicators in pixel format were also reclassified into five classes. The class boundaries are shown in Appendix D. The reclassified raster datasets are provided in Appendix E.

To explore the relationships between different indicators, a correlation matrix was generated at the district level (see Fig. 4), whereby the correlation was derived from the "Band Collection Statistics" tool in ArcGIS Pro. For this purpose, the mean values of the pixel-based data were aggregated to the district level using the "Zonal Statistics" tool in ArcGIS Pro and then reclassified into 5 classes using the natural breaks method. For new proxy indicators, the median values were aggregated to the district level as these have already been reclassified. The correlation matrix shows a stronger positive correlation for "Soil organic carbon" and "Consecutive dry days" which can be explained by the fact that organic matter is related to climatic conditions. In addition, "Soil organic carbon" shows a strong correlation with "Distance to main source of drinking water". However, we included all factors in our analysis as we assume that there is no causal relationship between the time taken to reach the main water source and organic carbon content. The integration of all data sets is described in the following section.

2.2.3. *Weighted overlay analysis*

The WOA is integrated as a tool in ArcGIS Pro for evaluating and ranking multiple factors within a given geographical area (ESRI, 2023). The tool assigns a weight to each raster layer in the analysis, reflecting its relative importance to the final output layer. The RII has been normalized to a value of 100 (see Table 1) to meet the technical requirements of the WOA. The higher the weight, the higher the influence of the layer on the final output layer.

For the WOA, the highest spatial resolution of each of the proxies was used. Feature classes were scaled from 1 to 5 within the weighted overlay tool, with 5 being the highest score. "No data" was assigned a value of 0. The resulting cell size was defined as 1 km for visual presentation and 100 m for the comparative analysis.

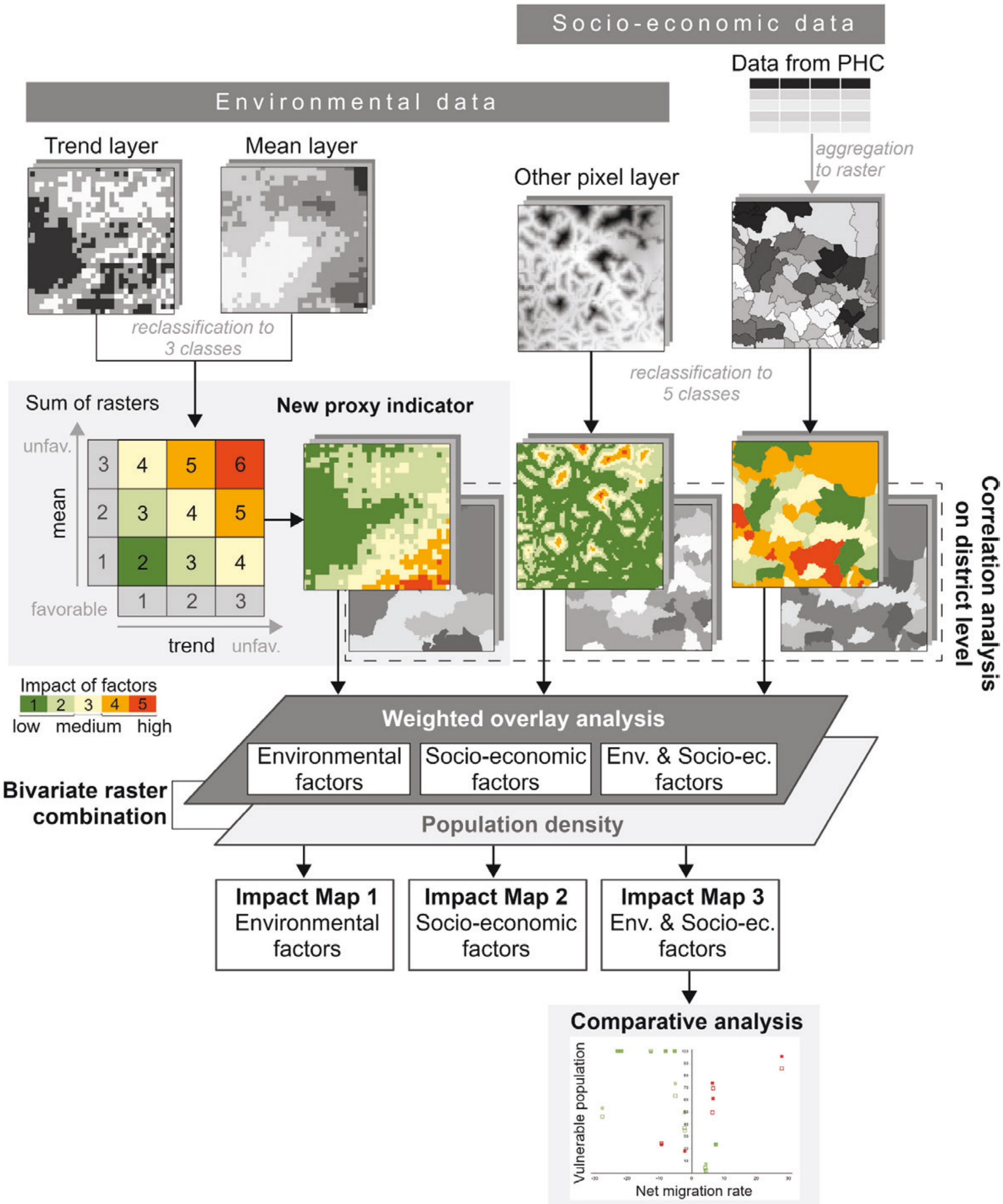

Fig. 3. Schematic workflow of spatial data reclassification and data integration into the weighted overlay analysis, PHC = Population and Housing Census, unfav. = unfavorable.

The output of a weighted overlay is a new raster in which each cell value represents the combined influence of the input rasters. The WOA was conducted separately for three distinct sets of factors: environmental factors, socio-economic factors, and a combination of both. The results were classified on a scale of 1 to 5, with values of 1 and 2 indicating a low impact, 3 representing a moderate impact and 4 and 5 reflecting a high impact of factors (see Fig. 3).

Bivariate maps (Brown, 2020) were utilized to combine the outcomes of the WOA with population density data. This integration allows to identify areas where a high impact of the factors coincides with a high rural population density. These impact maps demonstrate the influence of various socio-economic and environmental factors and highlight areas where these factors are most pronounced and thus the likelihood of migration is assumed to be more likely. For this approach, the population density (WorldPop & Bondarenko, 2020) was reclassified to three classes, which is shown in Fig. 1.

This study focused on the rural population as the main migratory and most vulnerable group. Therefore, settlements with more than 5,000 inhabitants (CIESIN, 2021), which represent the urban areas (GSS, 2014), were blacked out to avoid misinterpretation of the data.

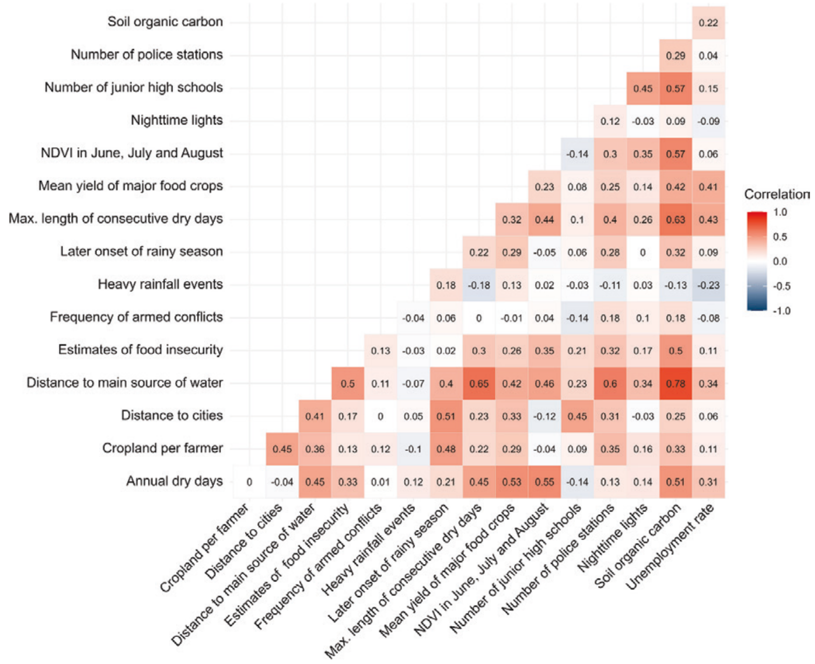

Fig. 4. Correlation matrix of proxy indicators.

2.2.4. Comparative analysis

Although validation of the results is not possible, a comparative analysis of net migration rates and affected population is suitable to verify whether the identified vulnerable areas are associated with the current net migration rates. Vulnerable areas are defined as areas with moderate to high impact of factors. If a region has a negative net migration and a high proportion of its rural population lives in vulnerable areas, it is reasonable to assume that the unfavorable conditions have led to out-migration. However, it is important to note that these two phenomena could also be independent of each other.

Net migration rates for the period 2010 – 2021 based on GSS (2023) were calculated at the regional level to verify if the impact maps accurately depict current migration patterns in Ghana. In this context, migrants are defined as individuals who have resided outside their place of birth for at least twelve months (GSS, 2023).

A population dataset (count of population in 100 m grid cells) developed by Schiavina et al. (2023) was used to compute, first, the proportion of the total population residing in areas with moderate to high impacts of adverse factors and, second, the proportion of the rural population. For this purpose, the extents of urban settlements were subtracted from the gridded population layer. The results were then plotted against the net migration rate (Fig. 6). Plausible results are expected when either more than one third of the rural population lives in vulnerable areas (areas with moderate to high impact of factors) and the region has a negative net migration rate, or less than one third lives in vulnerable areas and the region has a positive net migration rate. To better explain the results, we extracted the main migration flows for each region from the census (GSS, 2023), which are displayed in Appendix F.

3. Results

3.1. Weighted overlay analysis

The results of the WOA combined with the population density are visualized in Fig. 5. These impact maps show areas where unfavorable conditions coincide with densely populated non-urban areas, highlighting areas of high resource pressure and indicating a higher likelihood of migration.

The analysis revealed that the coast of Ghana, particularly the densely populated rural areas around the capital Accra, is moderately to severely affected by negative environmental factors (Fig. 5.1). The Upper West Region in northern Ghana experiences moderate to severe environmental pressures. Some of these areas are sparsely populated. However, in other parts of the north, particularly in the north-west, high levels of adverse environmental factors coincide with densely populated rural areas. A similar pattern is observed in the Northern, Northern East and Upper East regions, where the impact of environmental degradation ranges from moderate to high. In these regions, the results of the analyses show a high pressure of adverse environmental conditions that suggests a higher likelihood of migration. The Oti Region shows moderate impact combined with medium population density.

The Ahafo, Ashanti, Bono and Western North regions, all located in the semi-deciduous forest or rainforest zone, show the lowest impact of environmental factors. Although there are locations where there is a medium impact on populated areas, the majority of the population experience a rather low level of negative environmental conditions. Furthermore, these regions are the least constrained by socio-economic factors (Fig. 5.2), suggesting a low likelihood of migration driven by socio-economic and environmental factors. In the Western, Central, Eastern and Volta regions, there are certain areas where socio-economic factors have a medium impact and population density is high. On the other hand, the Upper East, Northern East and Northern regions exhibit a high level of negative socio-economic factors combined with a high population density, indicating a high likelihood of migration induced by adverse socio-economic conditions. This pattern is also evident in the western part of the Upper West Region. The Savannah and Bono East regions have a high impact score but mainly a low population density.

Taking into account all the factors analyzed (Fig. 5.3), certain areas stand out where the combination of these factors has a moderate to high influence, coupled with a high population density. Upper West, Upper East, Northern East, and Northern regions are most likely to experience

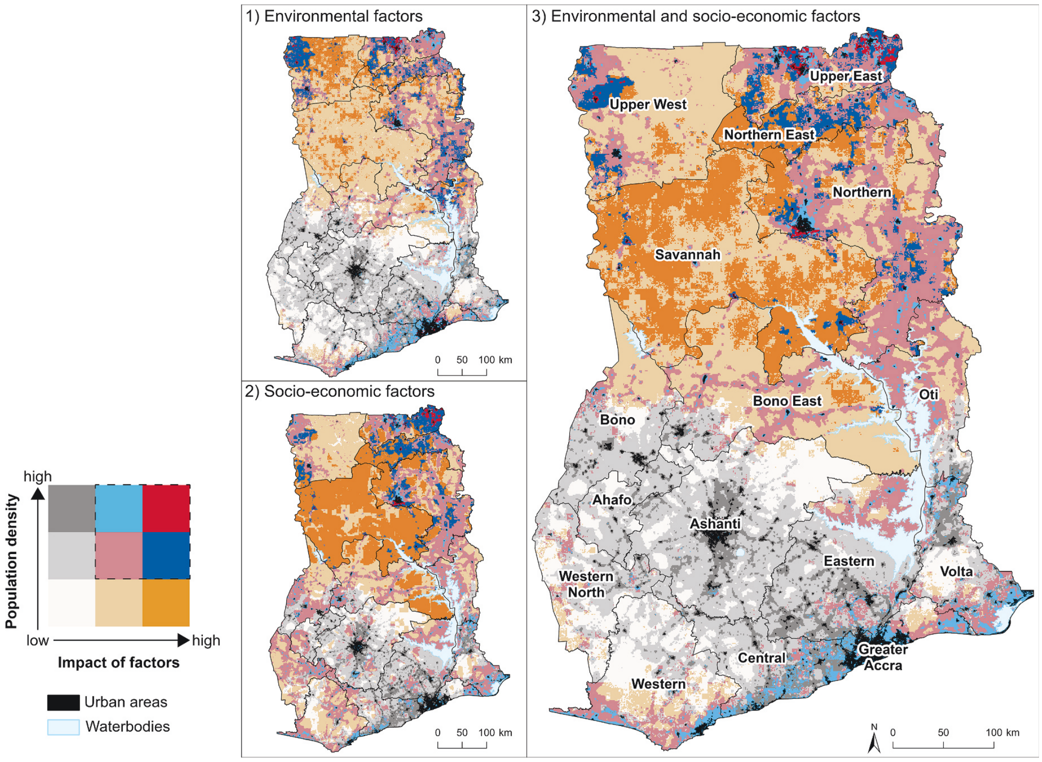

Fig. 5. Impact maps: Combination of rural population densities with 1) environmental factors, 2) socio-economic factors and 3) environmental and socio-economic factors. The dashed box in the legend highlights the colors that suggest a higher likelihood of migration.

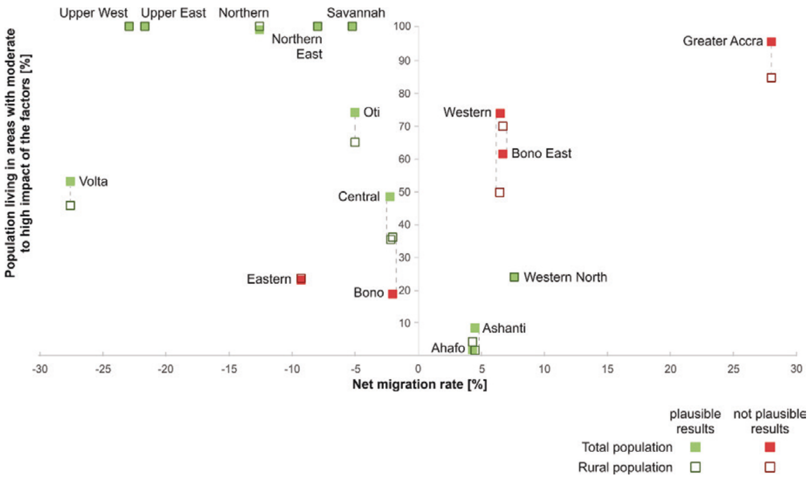

Fig. 6. Comparative analysis of the proportion of total and rural population living in areas with moderate to high impact of factors with the net migration rate for each of the 16 administrative regions. Filled squares represent total population and empty squares represent rural population. Related squares are connected by dashed line.

migration due to the unfavorable interaction of several factors. These regions show at least a moderate impact across a wide geographical area, affecting many inhabitants living in rural communities. Impacts are moderate in coastal areas, but affect large numbers of people in non-urban areas, mainly due to environmental factors. Conversely, Ashanti, Ahafo, Bono, Western North, and Eastern regions appear to be the least impacted by negative external influences, suggesting a lower likelihood of migration related to the factors studied.

3.2. *Evaluation of plausibility*

The proportion of the population living in vulnerable areas, based on the WOA with combined factors (Fig. 5.3), was compared with the net migration rate per region. The proportion of the rural population and the total population were indicated by the number of inhabitants per 100 m raster cell. The purpose of this comparison was to evaluate whether the produced maps reflect the migration rates described in GSS (2023). This comparative analysis is also a means to evaluate whether geodata can be used to assess spatial migration patterns.

Regions in northern Ghana have a negative net migration rate, meaning that more people leave the region than arrive. In these regions, 100 % of the rural population lives in areas that are moderately to severely affected (see Fig. 6). Furthermore, in Volta, Oti, and the Central Region, over a third of the population resides in areas that are moderately to highly affected by adverse factors. Notably, all these regions recorded a negative net migration rate. In contrast, in Ashanti, Ahafo and Western North, the proportion of the rural population affected by negative factors is relatively low (less than one-third). At the same time, a positive net migration rate was reported for these regions. It is worth noting that the results were somewhat contradictory in some regions. For instance, the Eastern Region had a rather high net migration rate, but a relatively small proportion of the rural population is exposed to unfavorable factors. Western, Bono East and especially Greater Accra Region showed a high impact of factors but a positive net migration rate, i.e. in-migration. Greater Accra Region attracts a large number of internal migrants, although the region is affected by negative factors to a moderate level and the majority of population is living in vulnerable areas. Looking at the main migration flows from GSS (2023) (Appendix F), Volta, Central and Eastern recorded an outflow of more than 100,000 people to the neighboring Greater Accra Region. Ashanti, which is less impacted by external factors, is the primary destination for migrants from the northern regions and Bono. In general, Fig. 6 shows that the majority of regions (12) display plausible results and that the proportion of the rural population affected corresponds to the respective net migration rate, suggesting that adverse external factors have an impact on migration.

4. Discussion

4.1. Vulnerable areas in Ghana with high or low likelihood of migration

The results show that vulnerable areas with a high likelihood of rural migration can be mapped using spatial data. Furthermore, we demonstrated that it is possible to effectively analyze and weight environmental and socio-economic factors influencing internal rural migration in Ghana. The study's reproducibility and transferability have been maximized to facilitate its use in similar contexts. These results can be linked to existing migration research, which suggests that migration decisions are influenced by, among others, macro-level factors (Adger et al., 2024). Furthermore, the study complements the aspirations-capabilities framework (Haas, 2021), by identifying local geographical opportunities, i.e. where socio-economic and environmental factors may shape the decisions of individuals in rural Ghana to migrate.

The results in regards to environmental factors are in line with the analysis conducted by Rigaud et al. (2021) on environmental-induced migration hotspots. However, some studies suggest that long-term environmental degradation influences migration decisions (Bohra-Mishra et al., 2014; Mueller et al., 2014) while others highlight more pronounced effects from short-term environmental shocks (Gray & Mueller, 2012). Given the diversity of individual decisions (Adger et al., 2024), it is to be expected that decisions can be triggered by shocks, but are favored by long-term developments. Most of our environmental indicators combine trends with the average condition, which thus indicate areas of increased variability and therefore a greater likelihood of shocks.

The WOA revealed that unfavorable conditions in environmental factors, i.e. high amount of dry days and land degradation, strongly impact the coastal region. At the same time, the Greater Accra Region is attracting the majority of migrants despite having a relatively high total population that is exposed to external factors. This can be attributed to the concentration of industries in Accra and Tema, which serve as economic hubs that offer employment opportunities and better living standards (GSS, 2023). However, this trend has serious implications for the future of the region. The perceived attractiveness of the Accra Metropolitan Region and surrounding urban areas imply that more and more people will move to these locations (Yeboah, 2021), while agricultural conditions around the city deteriorate (Akubia et al., 2020). This development poses a significant problem in terms of the supply of food and livelihoods for people in the peri-urban areas of Accra (Ashiagbor et al., 2019). In general, approximately one million people live in rural areas in the coastal region in Ghana. These communities often depend on agriculture and fishing for their livelihoods, making them particularly vulnerable to the effects of climate change and other environmental challenges (Addo, 2013; Yang et al., 2019). In addition, sea level rise, which is expected to increase in the coming years, is also a concern for these regions. Coastal cities such as Keta, Ada, Accra, Shama and Sekondi-Takoradi are already facing significant losses of settlements due to coastal erosion, which is expected to worsen in the future (Boateng, 2012; Rigaud et al., 2021). Nevertheless, the attractiveness of cities is superior to prevailing environmental conditions. In other words, the pulling factors may be more important than the driving factors, as already observed in Schürmann et al. (2022).

The vulnerability of the rural population in northern Ghana to a range of negative socio-economic impacts is exacerbated by adverse environmental conditions. The results are consistent with recent literature highlighting the search for better livelihoods and employment opportunities as the main drivers of migration (Arthur-Holmes & Abrefa Busia, 2022), but also acknowledges that environmental factors indirectly influence economic conditions e.g. through effects on the agricultural productivity (Black et al., 2011; Falco et al., 2019). Regions such as Savannah, Oti, or the Northern East Region show high proportions of vulnerable populations but relatively low negative net migration rates. This may be explained by individuals' attachment to their place of origin (Amoako et al., 2023; Balgah & Kimengsi, 2022) or by financial constraints that prevent migration (Schewel, 2020; Warner & Afifi, 2014).

The Ashanti Region is a major destination for internal migrants. Its favorable environmental conditions for agriculture and the presence of Kumasi, Ghana's second largest city, encourage people from rural areas to seek better economic prospects and access to services (Adu-Gyamfi et al., 2022; Oduro-Ofori et al., 2023). This is likewise true for the Western, Western North, and Ahafo Region, which are all located in the more developed and resourceful central part of the country. These regions attract many migrants due to industry, mining, and agriculture (GSS, 2023). Our findings underscore the region's low exposure to adverse environmental and socio-economic factors. As Fig. 6 showed, in Eastern and Bono Region the external pressure was not estimated to be high, yet the regions have a high negative net migration rate. This could likewise be explained by the appeal and proximity of urban areas (Accra and Kumasi respectively). In case of Eastern Region this observation could also be linked to a decline in cocoa production and diamond mining, as well as the closure of factories, which have contributed to the adverse economic situation in the region (GSS, 2023).

The GSS (2023) underscores the importance of upgrading and modernizing the agricultural sector in order to attract young people to pursue careers in agriculture and to generate more employment opportunities. Another approach is to promote agro-based industries, which create a stable market for agricultural products and provide job opportunities for the younger generation at the same time. To realize these objectives, the government of Ghana has implemented the "One District One Factory" policy (Ghana Government, 2017), which seeks to transform the country from an agrarian economy to an industrialized one. However, according to Mensah et al. (2021), the success of this policy depends on the country's ability to attract cleaner industries, enforce stringent environmental regulations, and increase environmentally-related taxes.

Policy makers should engage with local communities and organizations to identify people's adaptation needs and formulate tailored responses (Cobbinah, 2021). This approach is particularly important for promoting rural development. Although migration can offer people better living conditions and higher incomes, it is crucial to consider the potential negative impacts, especially in relation to migration governance. Strategic interventions to mitigate these impacts, such as managing urbanization, may be necessary (Sietchiping & Omwamba, 2020). Efforts to improve migration conditions should include initiatives to address land degradation (Hoffmann et al., 2022), investment in infrastructure and education (Somanje et al., 2020), and the strengthening of translocal networks that are important for the resilience of migrant communities (Sakdapolrak et al., 2024). It is also crucial to secure remittances as they are a significant source of income for many households (Steinbrink & Niedenführ, 2020). When designing safe and resilient cities, it is important to consider the needs of migrants. This is because their perception of risk, attachment to place, and aspirations can significantly impact their subjective well-being (Szaboova et al., 2022). These measures would not only address immediate challenges, but also contribute to the long-term well-being and resilience of both urban and rural populations. Understanding the challenges in places of origin can help formulate effective strategies to address the aforementioned issues at the source.

4.2. Limitations

Although this study provides important insights into the socio-environmental vulnerabilities that influence internal migration in Ghana, it has limitations in providing a comprehensive understanding of migration patterns. Migration decisions are not fully captured due to the inability to quantify key factors such as social networks, personal motivations, and aspirations. Vulnerability mapping, however, is influenced by data availability and the selection of indicators (Sherbinin et al., 2015). The study relies on an expert-based approach, which can be subject to certain biases. For instance, the perspectives of experts may not always reflect those of the broader population. Yet, the expert opinions on the external factors influencing migration captured in this study were broadly in line with the current literature (e.g. (Adger et al., 2021; Azumah & Ahmed, 2023; Schürmann et al., 2022) and provided a more nuanced understanding of the issue beyond the simple average weighting of proxy indicators. For example, the search for better economic opportunities, often cited as the main driver of migration, was consistent with the expert weighting. Nevertheless, there is a discrepancy between the high RII values assigned to environmental factors and the comparatively lower rankings given to certain socio-economic factors. This is particularly evident in regard to land availability. Although experts have ranked it as having a lower impact, it is often cited in migration studies as a significant factor affecting agriculture-dependent households in Ghana, particularly in the northern regions (Bonye et al., 2021; Sward, 2017; Nyantakyi-Frimpong & Kerr, 2017). The relatively high weighting of environmental factors is, however, consistent with studies that argue that environmental variability can have a significant impact on vulnerable populations, especially those dependent on agriculture (Asare-Nuamah, 2021; Dumenu & Obeng, 2016; Teye & Nikoi, 2022). Nevertheless, there is a continuing debate about the extent to which environmental factors influence migration decisions (Kaczan & Orgill-Meyer, 2020).

Uncertainties remain due to the fact that 4 out of 16 regions did not show plausible results in the comparative analysis. This finding could hint towards weaknesses in available data or data processing. While environmental data are not restricted to artificial borders, most of the socio-economic data used in this study are only available at the district level. This results in clear boundaries of different feature classes. Aggregating socio-economic data to the raster level is challenging, because it may not be evenly distributed within each district, potentially leading to bias in the aggregated data. However, Ghana is divided into 261 districts, which allows for spatially differentiated analysis. In order to disaggregate the information from the census data to actual population data, population density was overlaid with the WOA outputs. Using the "natural breaks" method (Jenks, 1967), each factor was reclassified to achieve a common scale and to accurately assess the magnitude of the proxy indicators. This approach ensures reproducible results and increases their reliability. Other reclassification strategies may produce different results. Some factors show a stronger positive correlation, in particular "Soil organic carbon" and "Distance to a main source of drinking water". These factors are also more strongly correlated with precipitation indices. However, we include all factors in our analysis because we argue that some correlations are not necessarily causal and that migration is influenced by a variety of interacting factors. The preprocessing of precipitation indices and NDVI values introduced a degree of inaccuracy, as shown in Appendix B. The biannual rainfall in southern Ghana cannot be fully captured by the cumulative rainfall anomaly method we used. In addition, heavy cloud cover during the rainy season results in missing values for the land degradation proxy.

The weighted overlay analysis demonstrates the relative importance of different factors. This means that in some areas, the high impact of one factor, such as the number of dry days in the Upper East region, may be offset by the minor impact of other factors, such as the occurrence of relatively few heavy rainfall events. Overall, the complex decision-making process for migration is influenced by a variety of factors, and the WOA allows these factors to be considered simultaneously. A comparative analysis of the net migration rates, and the impact maps may help to evaluate the plausibility of the results. However, an exclusive overlay is not sufficient for validation as both phenomena can coexist without influencing each other.

5. Conclusion

In this paper, a novel mixed-method approach using different spatial data sources was developed to map vulnerable areas with a high likelihood of migration in Ghana. The combination between proxy indicators that reflect unfavorable environmental and socio-economic conditions and incorporating spatially explicit population data provided a differentiated picture of the vulnerable rural population in Ghana. Comparison with net migration data from the most recent PHC emphasizes the plausibility of the results, suggesting that spatial data can be used to identify areas with a high likelihood of internal rural migration. In particular, the research highlights the vulnerability of rural areas in the northern regions of Ghana to adverse socio-economic impacts in combination with environmental degradation, which is reflected in their negative net migration rate. People living in the coastal zone are exposed to environmental impacts that could potentially worsen in the future and contribute to a decline in livelihood quality. A further exacerbation through increasing urbanization by in-migration and thus declining socio-economic conditions is expected. Personal aspirations, place attachment and perceived opportunities may explain results that are not immediately apparent. These include the high attractiveness of urban areas, despite the fact that they are potentially as vulnerable or even more susceptible to environmental or economic risks than rural areas of origin.

The study is subject to some limitations, such as the reliance on an expert-based approach, potential errors in the aggregation of socio-economic data in raster format, and the lack of individual-level data. However, the results suggest the applicability of spatial data combined with expert opinion to identify areas with high (or low) likelihood of migration for the case of Ghana. The proposed analytical framework can be applied to other West African countries with similar migration contexts and data availability. By identifying vulnerable rural areas that may lead to migration, particularly to urban areas, regional policies can be designed and implemented to mitigate the impact of adverse environmental and/or socio-economic conditions and support off-farm adaptation strategies as well as sustainable rural development. The findings can be placed in the broader context of existing migration frameworks, as they provide insight into the macro-level influences that shape migration decisions and identify geographical opportunities. As such, the results can contribute to improving migration analysis and management strategies for regional planning authorities in the future.

CRediT authorship contribution statement

Alina Schürmann: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft. **Janina Kleemann:** Methodology, Supervision, Writing – review & editing. **Mike Teucher:** Writing – review & editing, Methodology. **Christopher Conrad:** Conceptualization, Resources, Supervision, Writing – review & editing.

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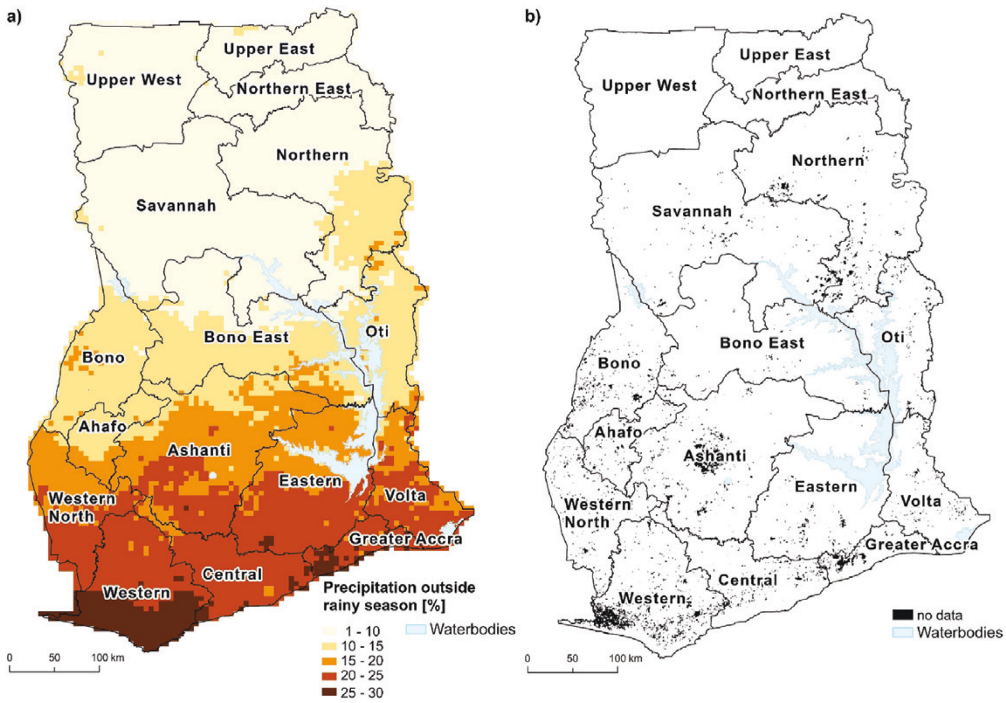
We express our sincere gratitude to all the interviewed experts for their valuable time and for sharing their experiences.

Appendix A. List of experts

List of experts. The years of experience refer to the respective interviewee.

Organization/Institution	Main topic of work	Years of experience
Adventist Development and Relief Agency (ADRA)	Returnees, potential migrants, sustainable livelihoods, education	10
CARITAS Ghana	Rural refugees/migration	>20
Catholic Action for Street children (CAS)	Street children/child migration	30
Centre for Popular Education and Human Rights (CEPEHRG)	Human right/health	>20
Challenging Heights	Internal migration, human trafficking, climate change impacts	8
Environmental Justice Foundation (EJF)	Climate change and modern slavery	4
Emperiks Research	Ensure sustainable livelihood and environment	3
Friedrich-Ebert-Stiftung Ghana (FES)	Social democracy, gender issues, climate change	>5
General Agricultural Workers' Union of Ghana (GAWU)	Agricultural issues	19
Green Africa Youth Organization (GAYO)	Climate change, environmental issues, empowerment of women	3
Ghana Refugee Board	Refugees	>20
Immigration Office Kumasi	Immigration issues	>10
International Organization for Migration (IOM)	Managing migration in Ghana	>30
Peasant Farmers Association Ghana	Proper agriculture policies, credit for farmers, land grabbing issues	16
School for Development Studies (SDS)	Migration from the Sahel to Ghana and internal migration	15

Appendix B. a) Uncertainties of rainy season calculation, b) missing pixels in the Normalized Difference Vegetation Index (NDVI) data



Appendix C. Reclassification of the proxy indicators that were combined to new indicator (Fig. 3), before integrating into the weighted overlay analysis. The trend layer was classified manually, the mean layer was classified using natural breaks (according to Jenks (1967))

		Class boundary		
Factor addressed in expert interview	**Proxy indicator**	**Trend** (Sen's Slope Estimator)	**Mean**	**Rank**
Increase of consecutive dry days (CDD) in rainy season	Maximum length of consecutive dry days	−1 - - 0.001	<38.34	1
		−0.001–0.001	49.96	2
		0.001–0.65	67.19	3
Permanent degradation of land/soils	NDVI in June, July and August	-0.079 - - 0.001	<0.58	3
		−0.001–0.001	0.72	2
		0.001–0.062	0.91	1
		no data	no data	0
Persistent droughts	Annual dry days	−0.999–0.001	<247.97	1
		−0.001–0.001	264.2	2
		0.001–0.44	295.48	3
Extreme rainfall events/flooding in the rainy season	Heavy rainfall events within the rainy season (days with precipitation >20 mm)	−0.33 - - 0.001	<12.01	1
		−0.001–0.001	15.88	2
		0.001–0.25	27.35	3

Appendix D. Reclassification of the proxy indicators used in the weighted overlay analysis based on natural breaks classification (according to Jenks (1967))

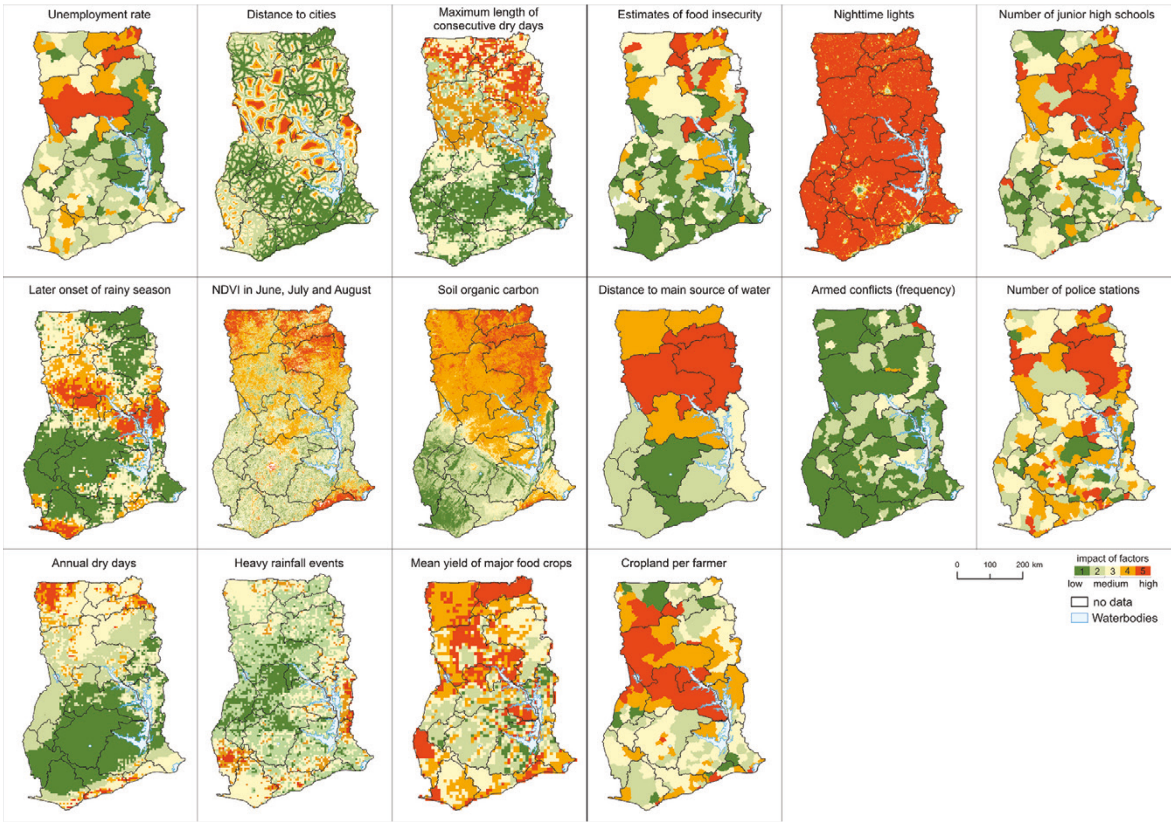
Factor addressed in expert interview	Proxy indicator	Class boundary	Rank
Job opportunities	Unemployment rate (%)	<9.2	1
		12.8	2
		16.6	3
		21.9	4
		45.9	5
Opportunities for trading	Distance to cities (travel time in minutes)	<153	1
		276	2
		433	3
		673	4
		1301	5
Environmental conditions for agriculture	Later onset of rainy season in days (Sen's Slope Estimator)	1.55	5
		0.7	4
		0.37	3
		0.1	2
		<0	1
Fertile soils	Soil organic Carbon (g/kg) in 0–20 m	no data	0
		26.1	1
		11.2	2
		9	3
		7.2	4
		<5.6	5
Agricultural production	Mean yield of 10 major food crops (amount of production per harvested area, in kg/ha)	11 814.1	1
		7366.4	2
		5096.3	3
		3474.7	4
		<1853.2	5
Food insecurity	Prevalence of severe and moderate food insecurity in the population [%]	no data	0
		<8	1
		16.4	2
		27.8	3
		46.4	4
		78.8	5
Poor infrastructure development	Nighttime lights in 2021 (average radiance)	75	1
		41.5	2
		24.4	3
		11.5	4
		<3.2	5
Access to education	Number of junior high schools per 1,000 inhabitants	39	1
		27	2
		22	3
		17	4
		<12	5
Access to water	Distance to main source of drinking water (minutes)	<16	1
		19	2
		24	3
		26	4
		33	5
Regular armed conflicts	Frequency of armed conflicts with fatalities	0	1
		2	2

(*continued on next page*)

(*continued*)

Factor addressed in expert interview	Proxy indicator	Class boundary	Rank
		5	3
		11	4
		12	5
Safety	Number of police stations per 100,000 inhabitants	29	1
		20	2
		15	3
		10	4
		<6	5
Access to farmland	Cropland per farmer (ha)	11.7	1
		5.5	2
		3.7	3
		2.6	4
		<1.2	5

Appendix E. Proxy indicators as input for the weighted overlay analysis, sorted by percentage of influence



Appendix F. The table shows the input data for Fig. 6, which includes the net migration rate and the proportion of people living in moderate to highly affected areas (vulnerable areas) based on Fig. 5.3. In addition, respective main out- and in-migration flow based on GSS (2023) are provided

Regions	Net migration rate	Total population in vulnerable areas [%]	Rural population in vulnerable areas [%]	Main out-migration flow	Main in-migration flow
Ahafo	4.3	2.0	4.4	Ashanti	Ashanti
Ashanti	4.5	8.3	1.8	Greater Accra	Upper East
Bono	-2	18.8	36.1	Ashanti	Upper West
Bono East	6.7	61.3	69.8	Ashanti	Upper West
Central	-2.2	48.4	35.5	Greater Accra	Greater Accra
Eastern	-9.3	23.2	23.5	Greater Accra	Greater Accra
Greater Accra	28	95.3	84.5	Central	Eastern
Northern	-12.6	99.3	100.0	Greater Accra	Savannah
Northern East	-8	100.0	100.0	Ashanti	Upper East
Oti	-5	73.9	64.8	Greater Accra	Volta
Savannah	-5.2	100.0	100.0	Ashanti	Upper West
Upper East	-22.9	100.0	100.0	Ashanti	Ashanti
Upper West	-21.7	100.0	100.0	Ashanti	Ashanti
Volta	-27.6	52.9	45.7	Greater Accra	Greater Accra
Western	6.5	73.4	49.7	Greater Accra	Central
Western North	7.6	24.0	24.1	Ashanti	Ashanti

Number of migrants
> 100,000
50,000 - 100,000
10,000 - 50,000
< 10,000

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4.3 Spatial assessment of current and future migration in response to climate risks in Ghana and Nigeria

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Objective:

To evaluate the applicability of the IPCC risk framework for mapping current and predicting future migration patterns in response to climate risks in Ghana and Nigeria.

Methodology:

Current and future risks that could result in migration were assessed by combining spatial environmental, socio-economic, and population data, including climate projections from CMIP6 models under the RCP4.5 scenario. The relevant factors were selected and weighted through expert consultations.

Key findings:

- Northern parts of Ghana and Nigeria exhibit elevated hazard, vulnerability, exposure, and overall risk scores, indicating a higher likelihood of migration.
- Perceptions of migrants suggest that socio-economic factors often influence migration decisions more than environmental factors, even in hazard-prone regions.
- Estimated future patterns indicate the persistence of current migration trends into the near future (2050).

Relevance to dissertation objectives:

The interplay between environmental hazards, vulnerability, and exposed populations was examined using the IPCC risk framework. Spatial data was incorporated to quantify the impact of external factors on rural out-migration. In line with objective 1, the study used expert interviews to rank the socio-economic and environmental factors relevant to migrants. Addressing objective 2, weighted factors that could have an impact on migrants were overlayed. This enabled the identification of current and future areas at heightened risk, where migration could be a response. However, actual perceptions of migrants only partially aligned with the identified areas prone to hazards. This indicates that, while geospatial analyses can be used to map current and future external factors, there is a need to account for the subjective aspect of migration, which spatial data alone cannot capture (objective 3).

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Spatial assessment of current and future migration in response to climate risks in Ghana and Nigeria

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West Africa's vulnerability to climate change is influenced by a complex interplay of socio-economic and environmental factors, exacerbated by the region's reliance on rain-fed agriculture. Climate variability, combined with rapid population growth, intensifies existing socio-economic challenges. Migration has become a key adaptive response to these challenges, enabling communities to diversify livelihoods and enhance resilience. However, spatial patterns of migration in response to climate risks are not fully understood. Thus, the study evaluates the applicability of the IPCC risk assessment framework to map and predict migration patterns in Ghana and Nigeria, with a focus on identifying areas of potential out-migration. By integrating geospatial environmental, socio-economic, and population data, the study highlights areas that have a higher likelihood of migration for the current baseline and near future (2050). Future climate is modeled using CMIP6 projections under the RCP4.5 scenario, while population projections providing insight into future exposure. The results from the baseline assessment are compared with actual migrant motivations, providing a ground-level perspective on migration drivers. In northern Ghana and Nigeria, elevated hazard, vulnerability, and exposure scores suggest a higher likelihood of migration due to the overall risk faced by the population. This pattern is projected to persist in the future. However, migrant responses indicate that environmental factors often play a secondary role, with vulnerability factors cited more frequently as migration drivers. The findings highlight the importance of developing localized adaptation strategies that address the specific needs of vulnerable areas. Additionally, management strategies that enhance community resilience and support sustainable migration pathways will be critical in addressing future climate-induced migration challenges.

KEYWORDS

climate change, exposure, geospatial data, hazard, internal migration, vulnerability, West Africa

1 Introduction

West Africa's exposure and vulnerability to climate change is shaped by the interaction of socio-economic, political, and environmental factors (Trisos et al., 2022). Approximately 60% of the West African workforce is employed in agriculture (Allen et al., 2018). The reliance on rain-fed agriculture increases vulnerability to climate variability, especially for rural households

(Sultan and Gaetani, 2016). In Ghana and Nigeria, the economies are heavily reliant on the agricultural sector, which is a key source of employment in both countries (Alehile, 2023; GSS, 2022a). In recent years, both countries have experienced increased frequency and intensity of droughts and floods, which have adversely affected agricultural productivity and food security (Owusu and Yiridomoh, 2021; Umar and Gray, 2023; Wrigley-Asante et al., 2019).

In both countries, the population is projected to grow significantly in the coming decades, further intensifying pressures on both agricultural and urban systems (Herrmann et al., 2020). As the population grows, the demand for food, water, and energy will rise, exacerbating environmental degradation and raising the risks associated with climate change (Simpson et al., 2023). Urban areas will be confronted with more people migrating to cities in search of better opportunities, increasing the density of informal settlements, poor sanitation and limited access to health care and education (Dick and Schraven, 2021). Rural areas, on the other hand, will face increased pressure on land and water resources due to population growth, potentially leading to more severe food and water shortages (Trisos et al., 2022). Rising temperatures and changing rainfall patterns could result in the unsuitability of current agricultural zones for staple crops such as maize, millet, and sorghum (Porter et al., 2014; Tomalka et al., 2021), which are of critical importance for food security and livelihoods in the region. Furthermore, increased evapotranspiration rates due to higher temperatures could exacerbate water scarcity issues, further challenging agricultural productivity (Tomalka et al., 2021). Climate-induced agricultural decline is likely to exacerbate existing socio-economic inequalities, as poorer households have fewer resources to adapt to changing conditions (Vinke et al., 2022).

In response to decreasing agricultural productivity, migration is often employed as an adaptive strategy, enabling individuals and communities to pursue alternative sources of income in urban areas or less affected rural areas (Adger et al., 2020; Borderon et al., 2019; Tuholske et al., 2024; van der Geest, 2011). By choosing to move to new locations or engaging in different economic activities, migrants can reduce their risks and enhance their resilience to environmental changes. Migrants often remit funds to their households in areas affected by climate change, providing a vital source of financial support for adaptation efforts (Maduekwe and Adesina, 2022). These remittance flows can help improve living standards, build infrastructure, and invest in sustainable practices that enhance resilience to climate impacts (Bendandi and Pauw, 2016).

It is likely that rural–urban migration will intensify, further contributing to the already pronounced urbanization trends in the region (Adamo, 2010; Serdeczny et al., 2017). However, migration itself can introduce new vulnerabilities, including social integration challenges, inadequate housing, and limited access to basic services in urban areas (Szaboova et al., 2023). In addition, people without financial resources or social networks may not be able to migrate, making them even more vulnerable to the adverse effects of climate change (Trisos et al., 2022). The ability of individuals, households and groups to make free and informed choices about whether, when and where to move or not to move is central to ensuring that mobility serves as an adaptation to climate change (Simpson et al., 2024). Simultaneous exposure to multiple stressors, including climate-related risks and other crises, can put translocal livelihood systems under severe pressure, potentially pushing them to their limits. Translocal livelihoods refer to the ways in which households and communities sustain themselves by using resources, networks and opportunities that are interlinked across different geographical areas (Steinbrink and Niedenführ, 2020). This interconnectedness allows households to diversify income sources, manage risks and access support from different places. However, when different parts of a migrant household face stressors simultaneously, their ability to coordinate, cope and adapt effectively can be compromised, leading to increased vulnerability and reduced well-being (Sakdapolrak et al., 2024).

In recent years, a growing body of research has focused on mapping vulnerability to various environmental and socio-economic risks (De Sherbinin et al., 2019). These studies employ spatial analysis to identify regions most at risk to hazards such as droughts (Ortega-Gaucin et al., 2021; Stephan et al., 2023) and floods (De Moel et al., 2015; Roy et al., 2021) or vulnerability due to climate change (Gupta et al., 2020; McMillan et al., 2024). The majority of the cited research is rooted in the risk assessment framework proposed by the Intergovernmental Panel on Climate Change (IPCC, 2014, 2022). Some studies also incorporate climate and/or population projections to map potential future risks (Dubey et al., 2021; Marzi et al., 2021). While this research has improved the understanding of where vulnerable areas are located, there is still a gap in the knowledge of the way people respond to these risks, particularly in relation to migration. How and where people move in the face of climate risks is not yet systematically understood (Szaboova et al., 2023). Nevertheless, spatial data indicating areas prone to such risks may help identify regions from which people are likely to relocate. Research on migration has often focused on environmental and demographic factors to identify migration hotspots (Hermans-Neumann et al., 2017; Mijani et al., 2022; Neumann et al., 2015).

To date, no study has applied the risk assessment framework specifically within the context of migration. Therefore, the study aims to evaluate the suitability of risk assessments to map and predict local migration patterns, with a focus on identifying areas of potential out-migration, both in the present and the future. To achieve this, multiple spatial datasets representing current and near-future conditions were collected based on expert knowledge and integrated into a framework proposed by Zebisch et al. (2023) based on the IPCC sixth assessment report (AR6). The results of the current state assessment were compared with the actual motivations of migrants from Ghana and Nigeria to provide a ground-level perspective on the factors driving migration.

While most studies using risk assessments have been conducted at the supra- and national or coarse subnational level (Ayodotun et al., 2019; Marzi et al., 2021), this study seeks to refine the approach by integrating environmental data with existing socio-economic vulnerabilities at a more localized administrative level. This approach provides a clearer picture of where communities might respond to the impacts of climate change and therefore targeted interventions can be developed to enhance the local adaptive capacity and/or provide sustainable support for inhabitants that choose to migrate.

2 Methods

2.1 Study area

Ghana, a lower-middle income country in West Africa, has a population of approx. 31 million inhabitants (GSS, 2021a). Ghana's economy is mainly driven by the agricultural sector, which employs 33%

of the workforce (62.9% when referring to the rural population), with a high dependency on rain-fed crops such as maize, millet, and cassava (GSS, 2022b; MoFA, 2021). The country faces challenges due to inadequate infrastructure and lacking access to essential services such as water, sanitation, and health care (GSS, 2021b). Cocoa is a key economic contributor, alongside other cash crops such as oil palm, cashew and rubber (Essegbey and MacCarthy, 2020). Ghana is divided into 16 regions (administrative level 1) and 261 districts (administrative level 2; see Figure 1).

The second country investigated is Nigeria, which is the continent's largest economy and most populous country with 236.7 million people (The World Factbook, 2021). Nevertheless, the poverty rate exceeds 50%, inequality is increasing, and the economy is vulnerable to fluctuating oil prices. Agriculture employs about 35% of the workforce, and the sector is heavily dependent on rainfall (Alehile, 2023). Ongoing conflicts, such as the Boko Haram insurgency in the north-east and unrest in the Niger Delta, are exacerbated by governance challenges that threaten the overall stability of the country (Berger et al., 2021). Climate change increases challenges in key sectors such as agriculture and hydropower, and disrupting food and water security (The World Bank Group, 2021). Moreover, Nigeria's rapid urbanization has led to the growth of informal settlements in cities such as Lagos and Abuja, where residents are exposed to various climate-related risks, including flooding and heat waves (Benjamin Obe et al., 2023; Ismail et al., 2024; Ndimele et al., 2024). Nigeria is divided into 36 states and 774 local government areas (LGAs). In both countries, the rural population's reliance on agriculture amplifies vulnerability to impacts of climate risks like poor crop yields due to droughts.

2.2 Framework

In this study, the risk assessment framework proposed by Zebisch et al. (2023) based on the IPCC AR6 was adapted to identify areas where climate-induced hazards interact with pre-existing vulnerabilities potentially leading to migration. McLeman et al. (2021) expanded this framework by viewing migration as part of a continuum of agency, emphasizing that migration decisions are shaped by perceived risks and available options. When local adaptation measures are not sufficient to reduce risk and a certain threshold is crossed - such as resource depletion or a decline in livelihoods - households may choose to migrate as a response. As outlined in the IPCC AR6, the determinants of risk include hazard, vulnerability and exposure (IPCC, 2021). Hazards, such as droughts or floods, intensified by climate change, threaten agriculture and food security in the region (Zougmoré et al., 2016). Section 2.4 details the newly generated data related to hazard indicators. Vulnerability refers to the susceptibility of a population to harm due to various socio-economic and environmental factors, such as poverty, lack of infrastructure, and limited access to resources. In West Africa, high agricultural dependency, combined with socio-economic challenges, amplifies the vulnerability of rural communities to climate impacts (Sultan and Gaetani, 2016). Vulnerability indicators are classified into 'sensitivity' (socio-economic/ecological) and 'capacity', as proposed by Zebisch et al. (2023). The newly generated data related to vulnerability indicators is detailed in Section 2.5. Exposure refers to the presence of people, livelihoods, and assets in hazard-prone areas. In West Africa, large segments of the population reside in regions highly susceptible to climate hazards, increasing their risk of adverse

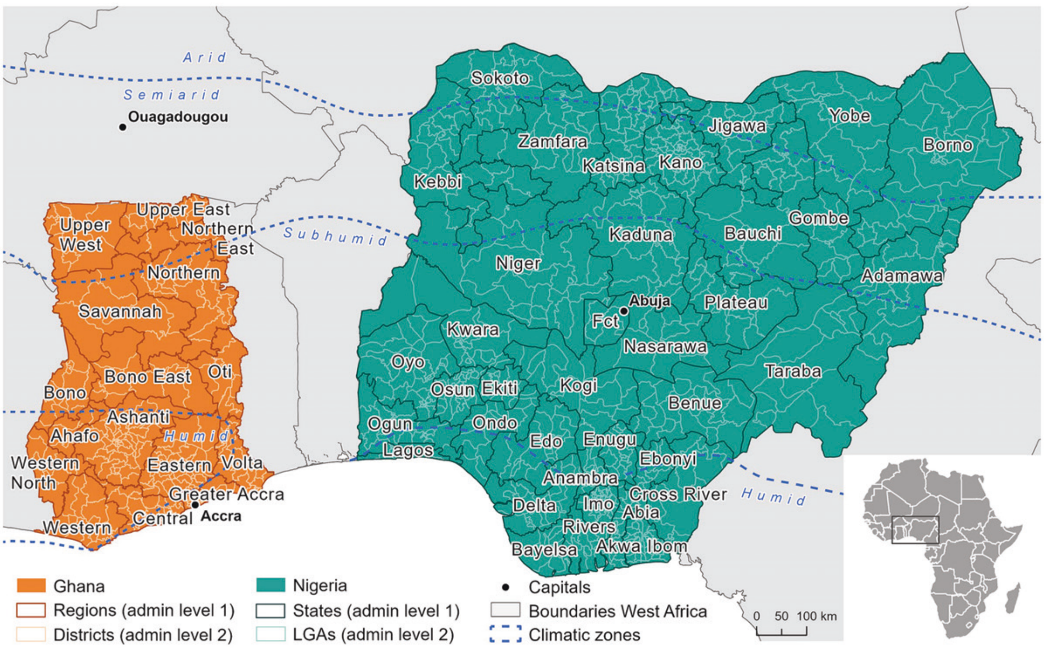

FIGURE 1
Focus countries with administrative levels and climatic zones. Fct, Federal Capital Territory.

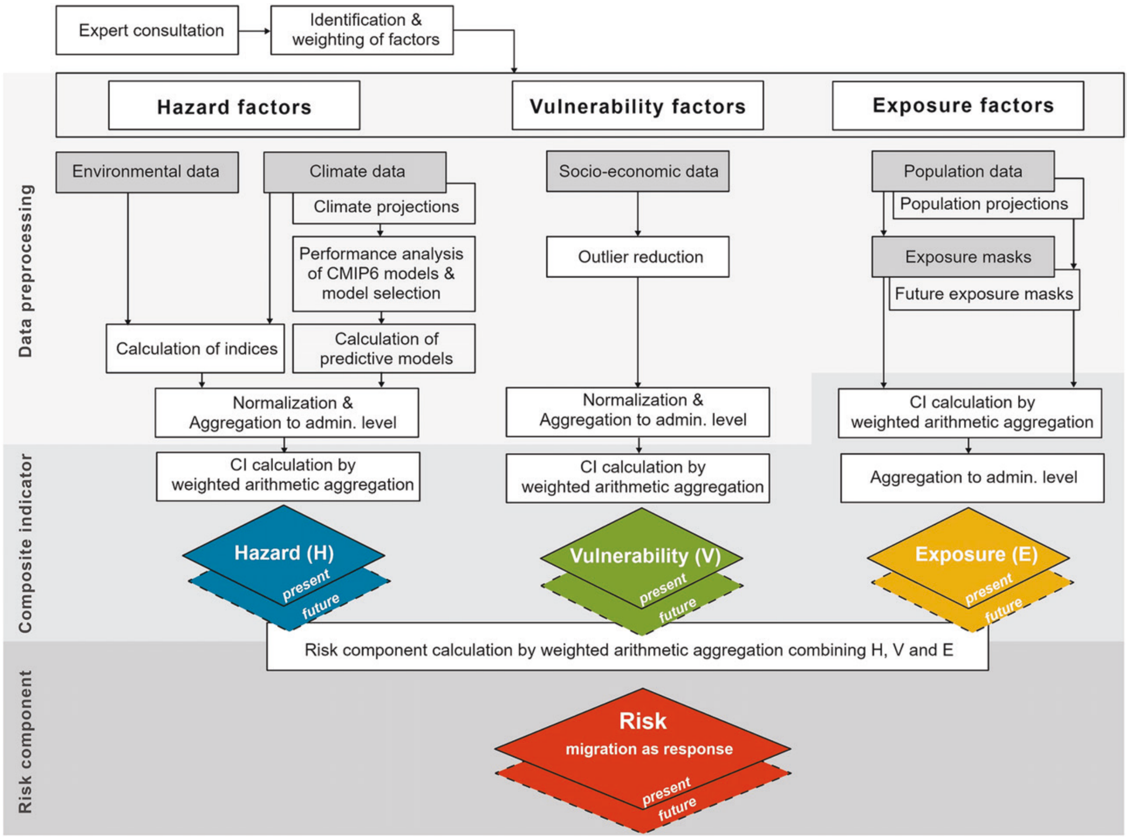

FIGURE 2
Overall workflow of present and future risk assessments. CI, Composite indicator.

impacts (Almar et al., 2023; Trisos et al., 2022). The data generated for exposure indicators is outlined in Section 2.7.

Migration is integrated into the risk assessment framework as a potential outcome resulting from the interaction of hazard, vulnerability and exposure. The overall risk is calculated using Equation 1:

$$\text{Risk}_{\text{present,future}} = \frac{(Hazard * w_H) + (Vulnerability * w_V) + (Exposure * w_E)}{w_H + w_V + w_E} \quad (1)$$

Where the present or future hazard, vulnerability, and exposure component are combined for the risk indicator and w_H, w_V, and w_E are the respective weights assigned to each component. The indicator selection for each component, along with their weightings, is described in the Section 2.3. For all components and the overall risk, values ≥0.6 are assumed to have rather negative impacts on the population (GIZ and EURAC, 2017). This threshold is used to identify areas where migration is more likely to occur compared to areas below this threshold. Migration is conceptualized as one of the adaptive responses that individuals and communities may choose to reduce their exposure to climate risks, increase their resilience, or seek better opportunities (McLeman et al., 2021).

This study focuses on the RCP4.5 scenario, a "middle of the road" pathway that projects a temperature rise of approximately 2.7°C by the end of the century (IPCC, 2023). This scenario aligns with the guidance from Zebisch et al. (2023) for the application of climate risk assessments. An overall workflow is illustrated in Figure 2.

2.3 Identification of relevant factors

In November and December 2023, two online workshops with experts from Ghana and Nigeria aimed to identify and weight key hazard, vulnerability and exposure factors that influence migration decisions in each country. The interactive tool Miro Board (Miro, 2024)[1] was used to introduce pre-defined factors from a literature review (based on Schürmann et al., 2022) to the participants. Four experts from Ghana and six from Nigeria reviewed these factors, with the option to modify, delete or add new factors, and to map connections between components. This process resulted in the identification of 11 hazard factors, 16 vulnerability factors and 10 exposure factors, although not all were relevant in both countries (e.g., fire events were important for Ghana but not for Nigeria). Some factors could not be included in the analysis due to unavailability of proxy indicators (see Supplementary Table S1).

1 www.miro.com

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Participants in these interviews were scientists from research institutes and NGOs with expertise in human migration and related research fields, particularly agricultural systems, rural and urban systems, food security, climate change risks, and adaptation strategies in their respective countries. The majority of the experts have more than 10 years of experience in their fields (Supplementary Table S2).

The "Budget Allocation" method (European Commission, 2023) was employed to weight these factors. Each expert was given a budget of 100 points to distribute among the factors for each composite category (hazard, vulnerability, and exposure) and for two time periods (the current situation as baseline and for 2050). This method enabled the experts to assign relative importance to each factor, allowing for equal weighting where necessary.

The median of the assigned budgets for each factor, for both countries and time periods, was normalized by dividing each value by the highest value across both the available present and future datasets. This approach allows to account for changes in the weightings over time. Table 1 lists the factors and respective proxy indicators used, and Figure 3 shows their normalized weightings.

2.4 Hazard assessment

2.4.1 Climate indices

The hazard composite indicator, primarily based on climate indices, required extensive preprocessing. For the present rainfall indices calculation, covering the period 1994–2023, we derived precipitation data from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS; Funk et al., 2015). The CHIRPS dataset, which covers Africa from 1981 to the present, combines satellite data with in-situ measurements at a 0.05° × 0.05° resolution, producing gridded precipitation time series that are well-suited for trend analysis and seasonal drought monitoring (Kouakou et al., 2023). The ERA5 reanalysis dataset (C3S, 2023; Hersbach et al., 2023) with 0.25° x 0.25° resolution was used to estimate daily maximum temperature and daily maximum wind speed with the latter calculated from the u- and v-components of wind at 10 m height.

In addition to calculating basic precipitation indices such as the number of heavy rainfall events, the factor "High rainfall variability" was proxied by the shifted onset of the first rainy season. A shift of the onset can have impacts on traditional planting schedules and crop growth cycles (Dunning et al., 2018; Van De Giesen et al., 2010). The rainy season onset was calculated pixel-wise for each year using an adapted method from Stern et al. (1981) and Laux et al. (2008), which defines the onset as the first day meeting three conditions: (1) at least 20 mm of rainfall is observed within a 5-day period; (2) the starting day and at least two other days within this 5-day period are wet (receiving at least 0.1 mm of rainfall); and (3) there is no dry period of seven or more consecutive days within the subsequent 30 days.

We calculated the future climate indices based on the difference of CMIP6 model projections (2021–2050) and historical CMIP6 data (1994–2014), which was then added to the respective present climate index. CMIP6 models were acquired from the Earth System Grid Federation's data portals (ESGF) CMIP6 archives.[2] Preselection criteria included their availability under the RCP4.5 scenario and a spatial resolution of at least 1.4° (~ 150 km), ensuring adequate pixel coverage over the study area in order to be able to analyze spatial differences, resulting in 13 models (Table 1). Historical simulations of daily precipitation, maximum temperature and maximum wind speed from 1994 to 2014 were utilized to assess the performance of the CMIP6 models, as not all climate models perform equally for each geographical location (Dembélé et al., 2020). Some models perform better for specific locations than others.

Therefore, the performance of the CMIP6 models in representing the main features of the West African climate was evaluated by comparing the precipitation, the number of days ≥35°C and maximum wind speed over the historical study period to observational data, using monthly averages as suggested by Romanovska et al. (2023). In case of precipitation, this approach allowed us to examine the models' capacity to capture seasonal distribution and accurately represent the bimodal rainfall regime characteristic of southern Ghana. CHIRPS data were used as the observational reference for daily precipitation, while ERA5 reanalysis data were used for daily maximum temperature and 10 m maximum wind speed.

Due to variations in the horizontal resolution of each dataset (see Table 2), bilinear interpolation was employed to standardize all model datasets to a 1° resolution (~110 km) before performance assessment. All models were harmonized to a 365-day calendar.

The outputs of the historical CMIP6 models were compared with the observational datasets for Ghana and Nigeria individually, using two performance metrics: Mean Absolute Error (MAE; Equation 2) and Kling-Gupta Efficiency (KGE; Equation 3). The MAE represents the mean of the absolute differences between the model predictions and the reference data, with lower MAE values indicating higher model quality (Willmott, 1982).

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|y_i - \hat{y}_i\right| \qquad (2)$$

Where n is the number of observations, y is the model data and y is the observational data. The KGE (Gupta et al., 2009) accounts for the model's correlation, bias, and variability compared to the validation data.

$$KGE = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma_m}{\sigma_v} - 1\right)^2 + \left(\frac{\mu_m}{\mu_v} - 1\right)} \qquad (3)$$

Where r is the Pearson correlation coefficient, σ is the standard deviation of model (m) and validation (v) which is the observational data, μ = arithmetic mean of model (m) and validation (v).

A model is selected if:

$$KGE_i \geq 0.5 \text{ and } MAE_i \leq MAE_{mean}$$

MAE_{mean} is the average of MAE values across all models. The results of the performance assessment and selected models can be found in Supplementary Table S3 and Supplementary Figure S1.

2 https://esgf-node.llnl.gov/search/cmip6/

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TABLE 1 The table presents the identified factors and their proxy indicators with information on data sources.

Factor	Proxy indicator	Direction	Source	Year (s)	Source	Year (s)	Availability per country	
			Present (2020)		Future (2050)		GHA	NIG
Hazard								
Decrease in average precipitation	Average precipitation	–	Funk et al. (2015)	1994–2023	CMIP6*	1994–2014 2021–2050	–	x
Drought	Average maximum length of consecutive dry days	+	Funk et al. (2015)	1994–2023	CMIP6*	1994–2014 2021–2050	x	x
Extreme temperature	Average number of hot days (≥35°C)	+	Hersbach et al. (2023)	1994–2023	CMIP6*	1994–2014 2021–2050	x	x
Fire	Number of fire events	+	Giglio et al. (2015)	2003–2023	N/A		x	–
Heavy rainfall events	Average number of days with ≥ 10 mm precipitation	+	Funk et al. (2015)	1994–2023	CMIP6*	1994–2014 2021–2050	x	x
High incidence of pests and diseases	Malaria Incidence Rate	+	Hay and Snow (2006)	2020	N/A		x	x
High rainfall variability	Average onset of rainy season	+	Funk et al. (2015)	1994–2023	CMIP6*	1994–2014 2021–2050	x	x
Loss in soil fertility	Trend of NDVI in July, August and September	–	Didan (2021a, 2021b)	2003–2023	N/A		–	x
Heavy wind events	Average maximum wind speed	+	Hersbach et al. (2023)	1994–2023	CMIP6*	1994–2014 2021–2050	x	–
Vulnerability								
Socio-economic or ecological sensitivity								
Conflict prone areas / insecurities	Number of conflicts (with fatalities)	+	Raleigh et al. (2023)	2014–2023	N/A		–	x
Dependence on agriculture (Poor economic situation)	People working in agricultural sector (GHA), Men in agriculture (NIG)**	+	GSS (2022a), Smits (2016)	2021	N/A		x	x
Demographic pressure	Sum of rural population per district	+	Wang et al. (2022)	2020	Wang et al. (2022)	2050	x	x
High food insecurity	Food insecurity per administrative unit	+	IPC (2023)	2023	N/A		x	x
Unfavorable soil conditions	Soil organic carbon (g/kg) in 0–20 m	–	Hengl et al. (2021)	2017	N/A		x	x
Adaptive capacity								
Lack of access to credit	Availability of microfinance Institutions per district	–	GSS (2021b)	2020	N/A		x	N/A
Lack of access to education	Available junior high schools per district (GHA) /Literacy of men (NIG)**	–	GSS (2021b), DHS (2018)	2020/2018	N/A		x	x
Lack of access to markets	Rural access index	–	CIESIN (2023)	2015	N/A		x	x

(Continued)

TABLE 1 (Continued)

Factor	Proxy indicator	Direction	Source	Year (s)	Source	Year (s)	Availability per country	
			Present (2020)		Future (2050)		GHA	NIG
Limited emergency preparedness plan	Ownership of technical device [%] per region	–	GSS (2022b)	2021	N/A		x	–
Exposure								
Population in drylands	Population in arid area (Ai <0.5)		Wang et al. (2022)/ Zomer et al. (2022)	2020	Wang et al. (2022)/ Zomer et al. (2022)	2050	x	x
Population living in coastal areas	Population living in low coastal elevation zones (<20 m)		Wang et al. (2022) / Farr et al. (2007)	2020	Wang et al. (2022) / Farr et al. (2007)	2050	x	x
Population living in flood prone areas	Population living in flood prone areas		Wang et al. (2022) / Nardi et al. (2019)	2020	Wang et al. (2022) / Nardi et al. (2019)	2050	x	x
Rural population	Population in non-urban areas		Wang et al. (2022)	2020	Wang et al. (2022)	2050	x	x
Smallholder	Rural population on cropland		Wang et al. (2022)/ Burton et al. (2022)	2020	Wang et al. (2022)/ Burton et al. (2022)	2050	x	x
Urban population	Population in urban clusters		Wang et al. (2022)	2020	Wang et al. (2022)	2050	x	x

The N/A notation in the column "Availability per country" indicates that data were not available, while the '–' symbol denotes that the factor was not identified as important during the expert consultation. GHA stands for Ghana, and NIG stands for Nigeria. "Direction" refers to whether a high indicator value represents high risk or low risk. *see Table 2 for detailed source description. **Only data for men were considered due to the limitations of the dataset.

Subsequently, we calculated each climate index for each selected model at the native resolution and then resampled the outputs to a 1° resolution. Then, the equal-weighted ensemble mean of each climate index across the selected models was calculated. This method reduces the impact of inconsistencies among different model outputs, thereby producing more reliable outcomes compared to reliance on individual models (Abel et al., 2024), as the models have different strengths in the performance of simulating extreme events or long-term changes (Klutse et al., 2021).

All climate indices were averaged over the respective time periods, and the differences between the predicted CMIP6 models and the historical CMIP6 models were calculated. These differences were added to the corresponding high-resolution observational datasets, such as CHIRPS or ERA5, after resampling the difference layer to match the resolution of the observational dataset using the nearest neighbor method. This method allowed us to generate predictive models with the high resolution of the observational data while incorporating climate model outputs. A simplified visualization of this approach can be found in Figure 4. The output of this approach can be found in Supplementary Figures S2, S3.

2.4.2 Loss in soil fertility

As an indicator of loss in soil fertility, the Normalized Difference Vegetation Index (NDVI) was used to assess vegetation vitality and productivity. This study combined NDVI data from the MODIS products AQUA (MYD13Q1; Didan, 2021a) and TERRA (MOD13Q1; Didan, 2021b) to produce 46 layers per year from 2003 to 2023. The Mann-Kendall test was employed to detect trends in soil fertility, using the *tau* as a proxy indicator. For this purpose, three-month median composites were created for June, July and August, representing the growing season of major food crops in Ghana and Nigeria (FAO, 2024a, 2024b). Pixels lacking information due to cloud cover were replaced by the median of a 5×5 moving window after these pixels were identified using the MODIS pixel reliability layer.

2.5 Vulnerability assessment

While data from the current census are available for Ghana, an attempt was made to identify corresponding equivalents for Nigeria. The future vulnerability component was calculated using the present-state vulnerability data in conjunction with their future weightings, given the unavailability of gridded or subnational data for future periods for both countries. In the case of demographic pressure, however, future projections were accessible for both countries. This factor was calculated by summing the rural population for 2020 and 2050 per district or LGA, as it is assumed that a high rural population, in particular, reflects the potential scarcity of resources. The aggregated datasets were then normalized using the global minimum and maximum, which is further explained in Section 2.6.

2.6 Data aggregation and index calculation of hazard and vulnerability component

To align with the method proposed by GIZ and EURAC, (2017) and Zebisch et al. (2023), each indicator was rescaled to a consistent range from 0.0 to 1.0, with higher values indicating more negative conditions for livelihoods. For the hazard component, first the indicators were aggregated to the

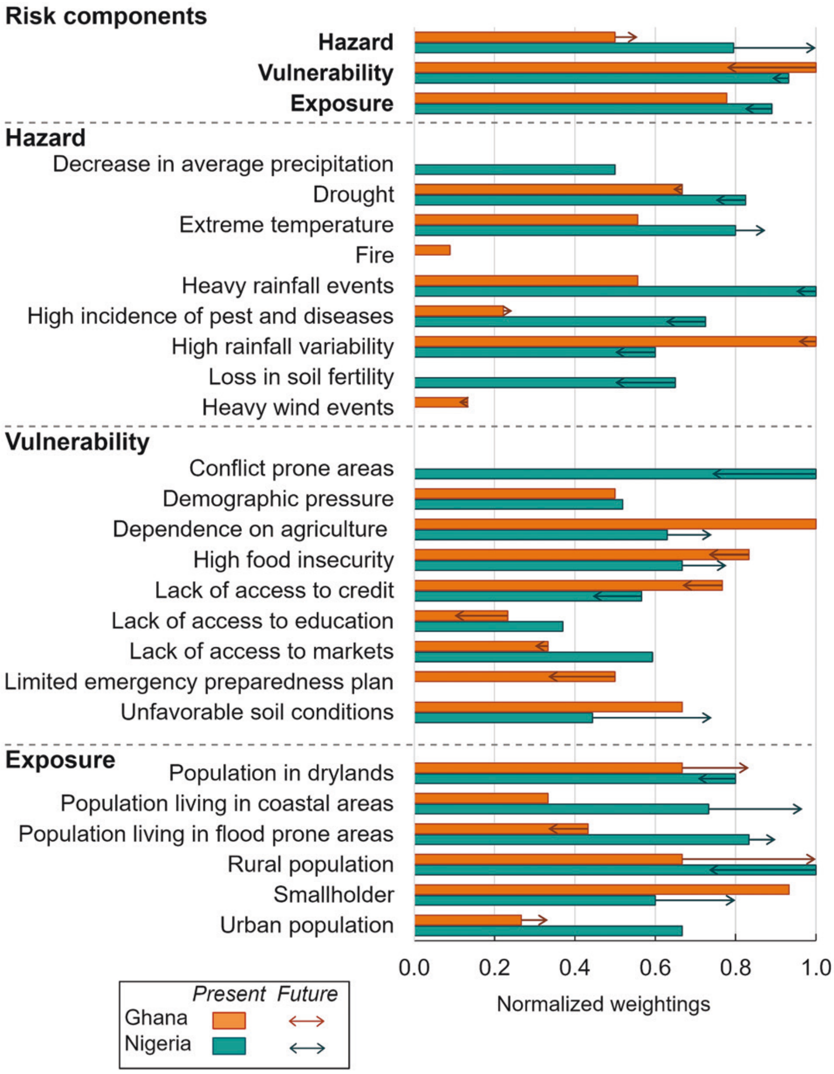

FIGURE 3
Composite indicators and respective identified factors with available spatial data and their weightings for the present and the future risk assessment. The bars indicate the present weighting, the arrows show the weighting for the future.

administrative level 2 boundaries (districts in Ghana and LGAs in Nigeria). In case of the hazard component with future predications available, a global normalization approach was used to normalize the aggregated datasets (see Equation 4), utilizing the minimum and maximum values across both the observational and predictive model time layers. This "global" normalization ensures comparability between present and projected future conditions.

$$X_{norm} = \frac{\left(X_i - \min\left(X_{obs}, X_{pred}\right)\right)}{\max\left(X_{obs}, X_{pred}\right) - \min\left(X_{obs}, X_{pred}\right)} \quad (4)$$

Where, X represents the input value, either from the observational dataset X_{obs} or the predicted dataset X_{pred}, $\min\left(X_{obs}, X_{pred}\right)$ denotes the minimum value across both datasets. The value $\max\left(X_{obs}, X_{pred}\right)$ is the maximum value across both datasets.

Other hazard indicators, which could not be predicted to the future were normalized according to the formula:

$$X_{norm} = \frac{\left(X_i - X_{\min}\right)}{\left(X_{\max} - X_{\min}\right)} \quad (5)$$

In case of a negative direction (when a high indicator value represents a low risk, e.g., in case of available microfinance institutions; see Table 1), the X_{nor} value was subtracted by 1.

As socio-economic factors may vary significantly between urban and rural areas, we first reduced outliers by identifying the 95th percentile. Any values exceeding the 95th percentile were replaced with

TABLE 2 CMIP6 global climate models used in this study, sorted alphabetically.

Model	Institute	Resolution	References
BCC-CSM2-MR	Beijing Climate Center (BCC) and China Meteorological Administration (CMA), China	1.1°× 1.1°	Xin et al. (2018)
CESM2	National Center for Atmospheric Research (NCAR), Climate and Global Dynamics Laboratory, Boulder, USA	1.25 × 0.94°	Danabasoglu et al. (2020)
CMCC-ESM2	Euro-Mediterranean Center on Climate Change- Earth System Model	1.25 × 0.94°	Lovato et al. (2022)
EC-EARTH3-CC	EC-EARTH Consortium (Europe)	0.7°× 0.7°	EC-Earth Consortium (EC-Earth) (2021)
EC-Earth3-Veg	EC-EARTH Consortium (Europe)	0.7 × 0.7°	EC-Earth Consortium (EC-Earth) (2019)
EC-Earth3-Veg-LR	EC-EARTH Consortium (Europe)	1.1°× 1.1	EC-Earth Consortium (EC-Earth) (2020)
FGOALS-f3-L	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University, China	1.3°× 1.0°	Yu (2019)
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory (GFDL), USA	1.3°× 1.0°	Dunne et al. (2020)
MIRO6	Japan Agency for Marine-Earth Science and Technology, Japan	1.4°× 1.4°	Shiogama et al. (2019)
MPI-ESM-1-2-HR	Max Planck Institute for Meteorology, Germany	0.9 × 0.9°	Gutjahr et al. (2019)
MRI-ESM-2-0	Meteorological Research Institute (MRI), Japan	1.1 × 1.1°	Yukimoto et al. (2019)
NorESM2-MM	Norwegian Climate Center, Norway	1.3°× 0.9°	Bentsen et al. (2019)
TaiESM1	Research Center for Environmental Changes (AS-RCEC), Taiwan	0.9 × 1.3°	Lee and Liang (2020)

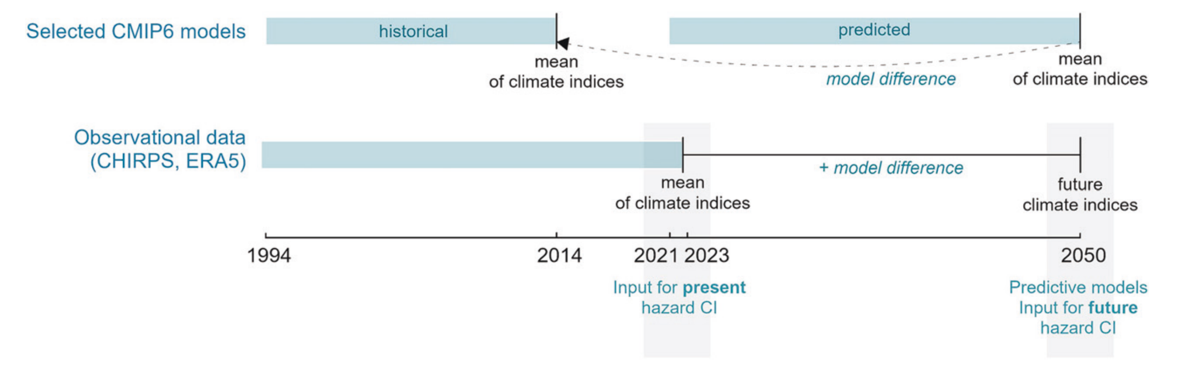

FIGURE 4
Visualization of future climate indices (predictive model) calculation. CI stands for Composite Indicator.

the value below this threshold. Subsequently, data were aggregated at the administrative level 2 boundaries and normalized according to Equation 5. The normalized hazard and vulnerability factors are displayed in Supplementary Figures S4–S6. To aggregate individual indicators into composite indicators, Zebisch et al. (2023) recommend using a 'weighted arithmetic aggregation'. This method involves multiplying each individual indicator by its respective weight, summing these products, and then dividing the sum by the total sum of the weights. This process is used to calculate the composite indicator (CI) of a risk component (see Equation 6).

$$CI_{present,future} = \frac{(I_1 * w_1) + (I_2 * w_2) + (I_n * w_n}{\sum_1^n w} \quad (6)$$

Where *CI* is the composite indicator for the *present* or the *future* (e.g., hazard), *I* represents an individual indicator of a component, *n* is the number of indicators, and *w* is the weight assigned to the indicator. The weights used were identified in the expert consultation (see Section 2.3) and are shown in Figure 3. If no future dataset was available, the present-day data were utilized for the future risk components, with their weighting adjusted based on expert opinions.

2.7 Exposure assessment

A gridded projected population dataset published by Wang et al. (2022) with a 1 km resolution for the years 2020 and 2050 was employed to assess the exposure component. This dataset had been developed using the Shared Socioeconomic Pathways 2 (SSP2) "middle of the road" scenario. Six exposure layers were created for each year to represent different population groups identified by the expert consortium as being particularly vulnerable and more likely to migrate in response to hazards (see Table 1; Figure 3). Urban areas were defined on the basis of the spatial extent of settlements (CIESIN, 2021). Thus, in Ghana urban clusters are defined as grid cells with a minimum population of 5,000 and a density of 500 people per km^2. For Nigeria, urban areas are characterized by a minimum population of 10,000 and a population density of at least 1,500 people per km^2. Rural areas were defined as non-urban areas. Farmers were represented by overlaying rural population data with cropland areas, reflecting the assumption that smallholders reside near their farmland. The spatial distribution of the exposure layers is illustrated in Figure 5. After clipping each exposure layer with the population raster, population density was reclassified to a value of 1 for densities equal to or greater than 50 inhabitants per km^2. This reclassification emphasized population distribution while minimizing misinterpretations from urban density outliers during normalization. The detailed population distribution for each layer and time period is provided in Supplementary Figure S7. Subsequently, these distribution layers were used to calculate the exposure component according to Equation 6. The gridded exposure component was then aggregated to the administrative boundaries using the 99^{th} quantile, allowing to map the most at-risk population groups and recognize that certain areas, such as drylands or rural regions, may face higher migration pressures from hazards. In order to quantify population growth within a district or LGA, we calculated the percentage difference between 2020 and 2050 using data published by Wang et al. (2022) (see Supplementary Figure S8), enabling more accurate assessments of population exposure.

2.8 Actual motivation of migrants

To assess whether high hazard and vulnerability scores align with migrants' actual motivations, we analyzed data from national interviews developed and implemented in Ghana and Nigeria by research teams from the University of Cape Coast (Ghana) and the Federal University of Technology Minna (Nigeria). Interviews with migrants, non-migrants and potential migrants were conducted between May and September 2022 in Ghana and between June and October 2022 in Nigeria. For this study, we focused specifically on the responses of migrants. The questionnaire gathered information on socio-economic status, migration histories, and perceptions of climate change, among other factors.

In this study we used responses to the question: "What are the main reasons why you left your most recent place of origin/last destination?," allowing multiple answers for migration motivations. This was combined with the question" Where was your place of origin before migrating to this current destination?" which provides information about the respondents' places of origin (see Supplementary Tables S4, S5). For Ghana, 1,265 interviews were available while for Nigeria, 472 interviews were considered.

The spatial patterns of hazard and vulnerability scores was compared with the migrants' actual motivation. We calculated the proportion of respondents identifying environmental factors as the primary reason for migration to compare with the hazard component. For the vulnerability component, we summed the proportion of respondents citing "job opportunities," "access to markets," and "education" as their main migration motivations, with "insecurity" also included for Nigeria. For each region (Ghana) or state (Nigeria), we identified the highest hazard and vulnerability scores and plotted them against the normalized motivation scores. This method enabled both visual and quantitative evaluations of how well perceived migration motivations aligned with the calculated risk components. In order to compare the risk scores with actual migration rates, we plotted the current net migration rates for Ghana from the Population and Housing Census (Ghana Statistical Service (GSS), 2023) against the maximum risk scores per region. As this data was not available for Nigeria, we have included the outcome for Ghana in Supplementary Figure S9.

3 Results

3.1 Findings from the expert consultation

A total of 36 individual factors were identified during the expert consultation, of which 24 are included in the analysis due to data availability (Figure 3). Among these, nine factors related to hazards were identified. The Ghanaian experts considered 'Decrease in average rainfall' to be similar to drought, leading to the inclusion of only the drought indicator for Ghana. High rainfall variability in Ghana and high rainfall events in Nigeria were considered to have a highest impact on the agriculture-dependent population; in the present and in the future. For vulnerability factors, 'conflict prone areas' was mentioned only by the Nigerian experts, while 'limited preparedness for emergencies' was only highlighted for Ghana. Conflict is seen as having the greatest impact on the decision to migrate in Nigeria at present and in future, while in Ghana the reliance on agriculture is attributed to a high vulnerability. In Nigeria, people living in coastal and flood-prone areas are expected to be more exposed in the future, while in Ghana, people living in rural and arid areas are expected to face higher levels of exposure.

3.2 Ghana

For reasons of comprehensibility, the results are discussed at administrative level 1 (regional level for Ghana, Figure 6, and state level for Nigeria, Figure 7), although they have been visualized at administrative level 2 (district level for Ghana and LGA level for Nigeria). The highest hazard scores (≥0.6) in the current assessment are observed in districts located within the Upper East, Upper West, Northern East, and Northern Region. In contrast, the lowest hazard scores are concentrated in the central regions, including Ashanti, Eastern, and Central Region. Overall, hazard scores are predicted to increase across all districts in the future, except in some districts at the coast. The greatest increase is expected in the central regions, attributed to an increase of consecutive dry days and heavy rainfall events as well as a later onset of the rainy season. Highest vulnerability scores are observed in the Northern, Northern East, Savannah and Bono North regions, with values above 0.7, reflecting a high degree of negative impact of pre-existing adverse socio-economic conditions and low adaptive capacity of people. Factors contributing to this high vulnerability include a large agricultural workforce, limited access to education, and unfavorable soil conditions, specifically low organic carbon content. Conversely, the Greater Accra and Ashanti Regions exhibit the lowest vulnerability, or, more specifically, the highest adaptive capacity, due to better access to education and the presence

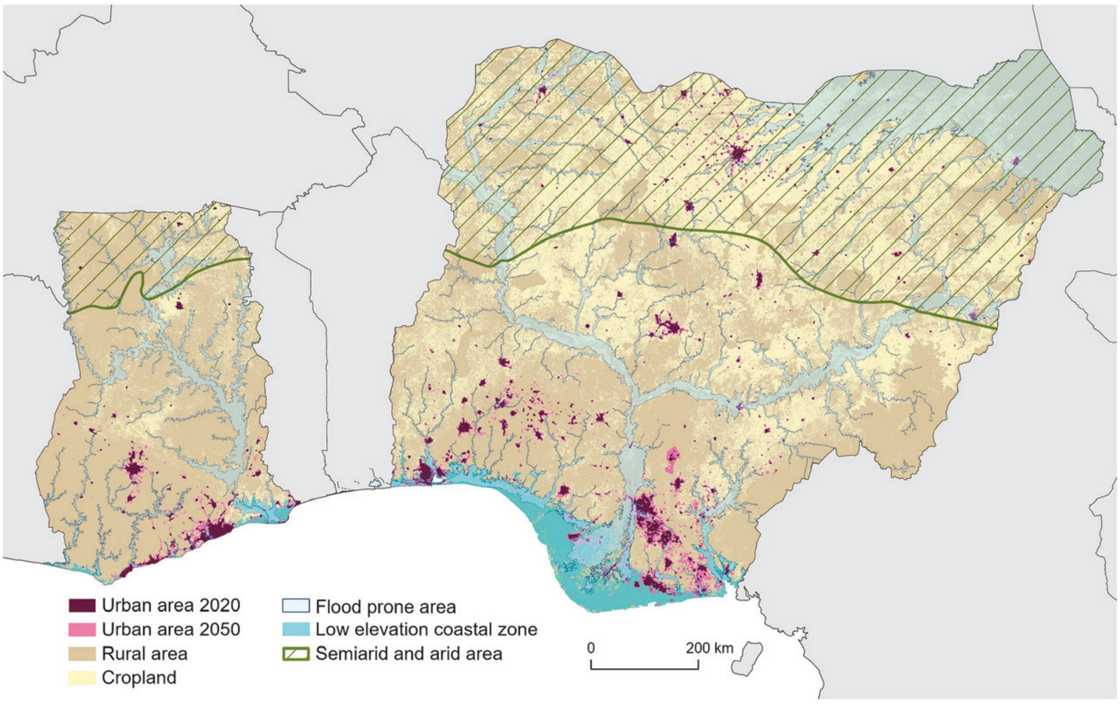

FIGURE 5
Spatial distribution of exposure layers.

of microfinance institutions. While most of the input data for both present and future vulnerability scenarios remain consistent, changes in the weighting of variables contribute to a shift in vulnerability patterns. Although the future vulnerability is distributed in a similar way to the current situation, a closer look at the differences reveals an upward trend, especially in the central regions. This is attributed to increased rural population.

Exposure is most pronounced in arid and rural areas, resulting to highest exposure levels in northern Ghana. These regions have a more arid climate and a higher proportion of arable land, which contributes to their higher exposure levels. Low exposure in the Savannah region is attributed to the low population distribution. While exposure in the northern regions is increasing, some coastal districts are experiencing a decline in exposure due to urban expansion, as urban areas are classified as less exposed compared to rural regions. An analysis of the percentage of difference in the population between 2020 and 2050 for Ghana and Nigeria (see Supplementary Figure S8) reveals a notable population increase in the central and southern regions of Ghana, particularly around districts that are already urbanized. In northern regions where an increase in risk has been calculated, the percentage difference is not as high as in the rest of the country, but still within a 20–40% range.

Finally, the risk component shows the combination of all three components, indicating high risk scores in the northern regions of Ghana, especially in the Upper East and Northern East Region. Those regions maintain their high-risk status in the future, while some districts within these regions are experiencing even higher scores. Risk scores are increasing in the majority of the regions, especially in the Upper West and Savannah regions.

3.3 Nigeria

In Nigeria, there is, like in Ghana, a north–south gradient in hazard scores, with generally higher scores in the northern regions compared to the south (Figure 7). In the present scenario, Sokoto, Kebbi and Borno states display the highest hazard scores, which are projected to increase due to higher temperature and more heavy rainfall events (see Supplementary Figure S3). Both factors received a high weighting in the future by the experts. Some states in Nigeria show a low decrease in hazard scores in future. The observed decline in the map of difference for hazard in parts of the Sudano-Sahelian Zone can be attributed to the relatively low number of hot days and an accompanying lower increase, in comparison to other regions of the country. The relatively low values observed along the coast can be attributed to the fact that temperatures do not rise as high, and heavy rainfall events do not increase as much, as they do in the northern regions. Additionally, these areas typically experience higher precipitation levels than the northern regions, which are expected to increase slightly in the future. High vulnerability scores are most pronounced in Borno and Zamfara, with Borno being particularly affected by a high number of armed conflicts—and being a factor of socio-economic sensitivity. An increase in vulnerability is predominantly observed in the northern states, while the reduction in Borno's vulnerability is primarily attributed to a lower weighting of conflicts for the future by the experts compared to the present (see Figure 3). In general, the majority of vulnerability factors are assigned with a higher weight, which leads to an overall increase of vulnerability scores in the future scenario. The northern regions exhibit the highest levels of exposure, which can be attributed to the high proportion of people living in arid or semi-arid areas and of population being engaged in agricultural activities. Furthermore, elevated levels of exposure are observed in certain coastal states like Lagos, Delta or Bayelsa, a pattern that is anticipated to intensify in the future due to population growth. On the contrary, in the central and northern part of Nigeria, the exposure score is predicted to decrease slightly. In Nigeria, the population growth is generally higher than in Ghana (see Supplementary Figure S8). It is notable that the north is experiencing a particularly strong increase in population, e.g., in Kano and Katsina state. This growth is accompanied by an overall increase in risk in these regions, driven by an increase in hazards and vulnerability. By 2050, the population of some southern LGAs is expected to double, contributing to higher exposure scores as more people inhabit areas with elevated exposure risks. The states with high overall risk in both the present and future remain largely unchanged, with further intensification in Yobe and Kebbi State. In contrast, some states in the southern part of Nigeria, such as Oyo, Ondo, and Cross River, are expected to experience a decrease in risk.

3.4 Comparing hazard and vulnerability scores with actual migrant motivations

The relationship between present hazard and vulnerability scores and migrants' motivations is illustrated in Figures 8, 9 for Ghana and Nigeria, respectively. It is important to note that, overall, relatively few

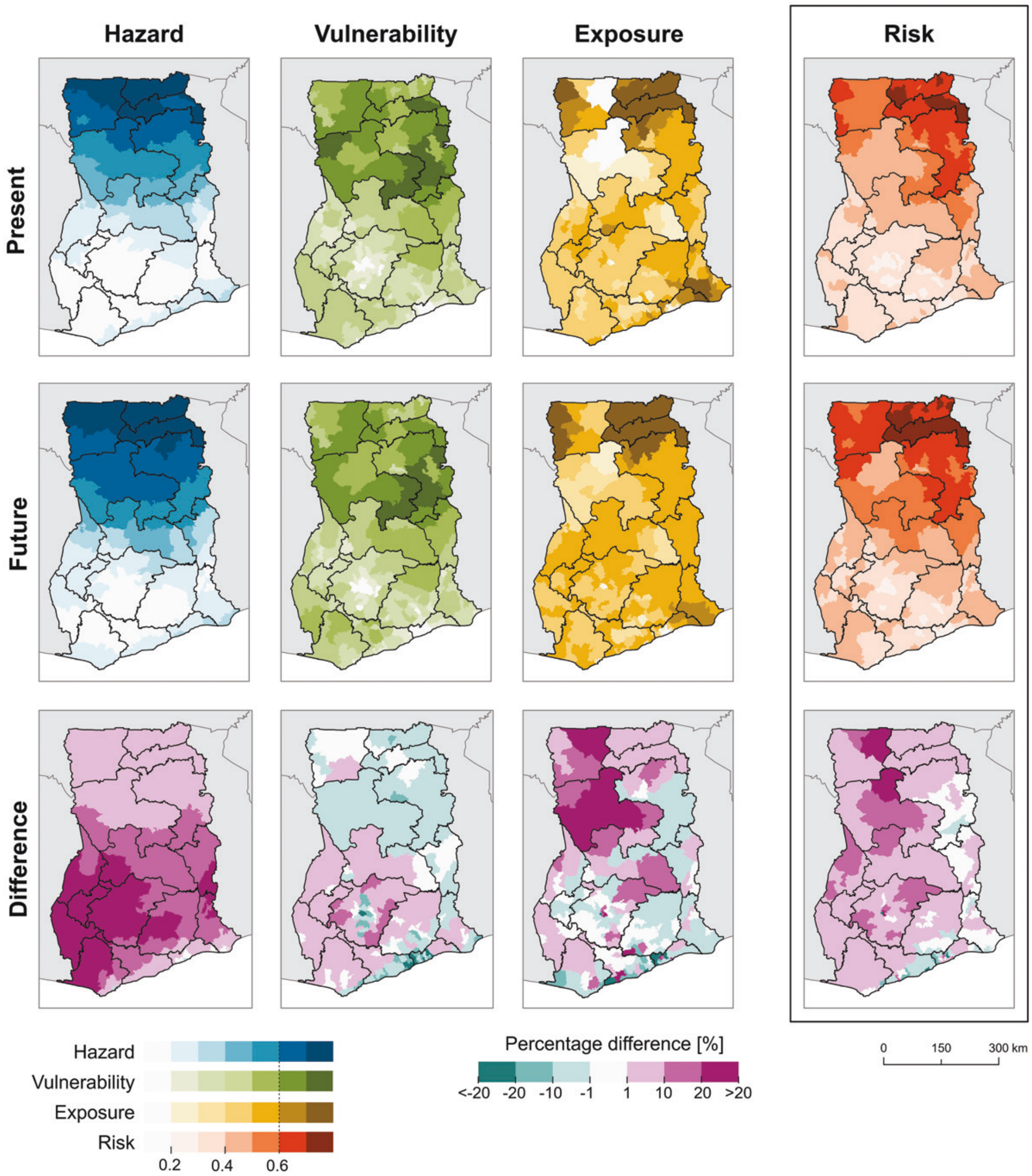

FIGURE 6
Risk assessment for Ghana. The risk map (right side and red map) shows the combination of the hazard, vulnerability and exposure maps. The darker the colors the higher the risk score.

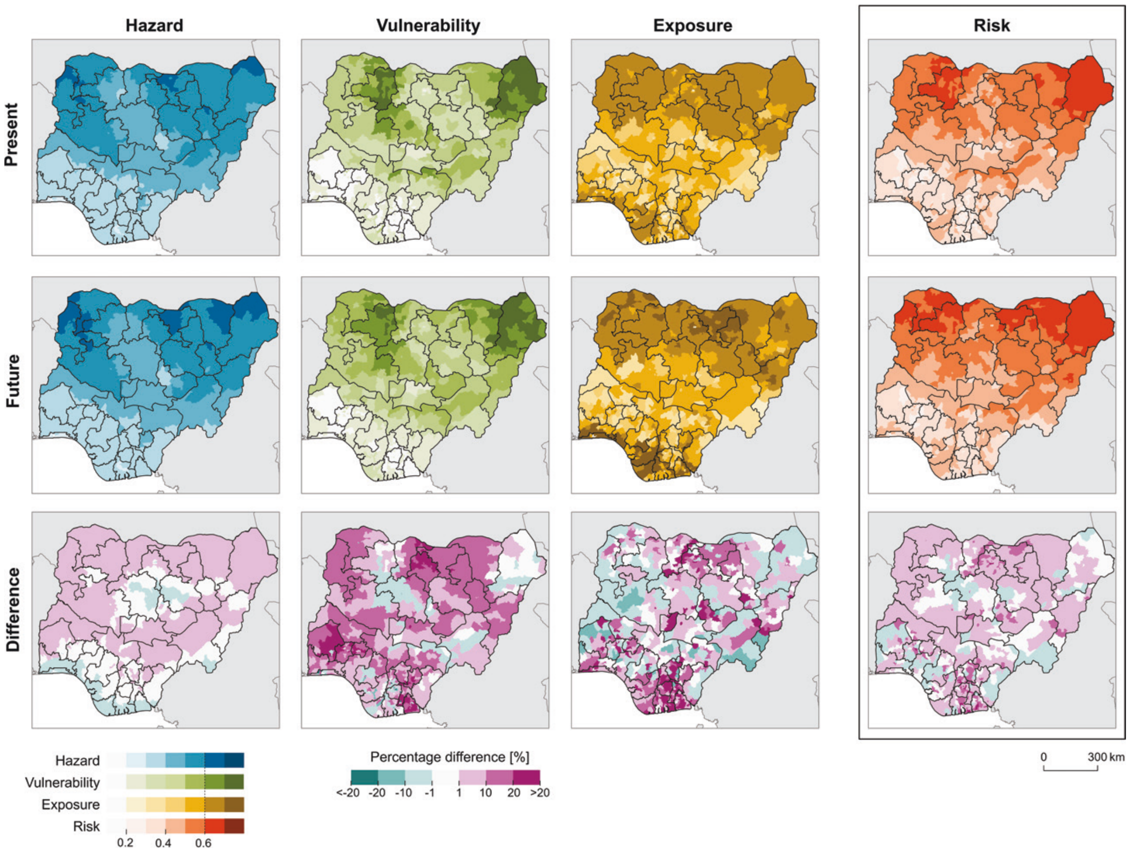

FIGURE 7
Risk assessment for Nigeria. The risk map (right side and red map) shows the combination of the hazard, vulnerability and exposure maps. The darker the colors the higher the risk score.

migrants cited environmental factors as their primary reason for migration. In Ghana, the highest percentage of respondents citing environmental reasons within any region was 14.5%, while in Nigeria, the highest percentage within a state was 33.3%. In contrast, socio-economic factors related to vulnerability were cited more frequently, with the highest percentage being 74.5% in Ghana and 100% for Nigeria. This analysis aims to determine whether regions or states where migrants more frequently cited environmental or vulnerability related factors correspond to those with higher hazard or vulnerability scores.

In Ghana, migrants more frequently identified environmental factors as a primary reason for relocating from regions with high hazard scores (≥0.6). Conversely, migrants from regions with lower hazard scores less often attributed their migration to environmental conditions. Socio-economic factors are prevailing reasons for migration in regions characterized by both high vulnerability and hazard scores. This suggests that economic factors often play a crucial role in migration decisions, especially in regions facing environmental challenges.

In the case of Nigeria (Figure 9), states with high hazard scores, such as Borno, Sokoto, Zamfara, and Yobe, environmental factors did not exhibit a higher frequency of migrants citing environmental factors as their reason for migration. Instead, socio-economic factors were identified as key motivations for migration. In states such as Borno and Sokoto, where both high vulnerability scores and high hazard scores were calculated, socio-economic factors were identified as the primary motivation for migration, rather than environmental factors. This indicates that environmental-related stressors may not be perceived as direct threats by the population, but rather as contributors to deteriorating economic conditions, which subsequently drive migration. The indirect impact of environmental changes on livelihoods likely results in people prioritizing economic motivations over environmental ones when explaining their migration decisions. This underscores the complex interplay between environmental stressors and socio-economic conditions in shaping migration patterns.

4 Discussion

4.1 Discussion of results

The risk assessment framework is able to account for the interplay of environmentally related hazards, vulnerability (especially socio-ecological sensitivity and low adaptive capacity) together with exposed population groups. The study intends to quantify the impact of external factors influencing rural out-migration by integrating spatial data in order to identify areas where migration is more likely to occur.

However, it is important to acknowledge that numerical values of thresholds are not absolute reflections of reality. Migration decisions may occur in regions independently from counted data or numerical thresholds, while some individuals may choose to stay in areas even though these areas are scientifically classified as high-risk areas. While adverse climate events can create conditions that lead individuals or communities to consider relocation, their decision to stay is often influenced by a range of factors. For example, many vulnerable communities use local coping strategies, such as diversifying livelihoods or adapting agricultural practices, to address climate-related challenges and reduce the need to migrate (van der Geest and Warner, 2015). In addition, strong community ties and deep cultural attachments may support a preference to remain in place despite certain risks (Kutor et al., 2025). Nevertheless, the method provides a systematic approach to linking spatial datasets and projecting shifts between current and future migration patterns. An increase in the risk score does not necessarily indicate that a greater number of people will migrate from these regions in the near future. Rather, it suggests that living conditions in these regions are deteriorating due to factors such as increased rainfall variability or greater resource pressure from a growing rural population, which is further compounded by existing socio-economic vulnerabilities. Nevertheless, this could also indicate that rural-to-urban migration may intensify in the future, placing greater strain on urban areas.

The results of our analysis for the present state are largely consistent with statements from migration studies, which indicate that areas in northern Nigeria and Ghana are the primary areas of internal out-migration (Alarima, 2019; Ango et al., 2014; GSS, 2023; Schürmann et al., 2024; van der Geest, 2011). Main destinations for internal migrants in Nigeria are often economically vibrant states such as Lagos and the Federal Capital Territory (FCT) around Abuja, which attract people seeking better job opportunities and living conditions (UN, 2023). For most LGAs in Lagos State, we computed an increase in vulnerability and exposure scores due to the growing rural and urban population, as well as the state's coastal location, which will be more vulnerable to floods and rising sea level in the future (Adegun, 2023). Most internal migrants in Ghana move to Ashanti or Greater Accra Region (GSS, 2023), both of which have low risk scores. However, it should be noted that this study does not account for coastal flooding and erosion, which are expected to increase in the future and could impact coastal cities like Lagos or Accra (Rigaud et al., 2021).

The ongoing instability in northern Nigeria due to terrorist activities poses an additional layer of complexity. Although more rainfall is projected for the Sahel zone (Almazroui et al., 2020; Stanzel et al., 2018; Weber et al., 2023), which could improve yields for certain crops as cassava, groundnuts or rice, but at the same time potentially decrease yields for maize and millet (Tomalka et al., 2021). Even with potentially better agricultural conditions in the Sahel, the socio-political factors may continue to drive vulnerability and therefore rural out-migration. Studies have shown a correlation between increased rainfall and reduced conflict in communities. However, as rainfall becomes more variable and adaptation to these changes becomes more difficult, the potential for conflict may increase (Coulibaly and Managi, 2022; Nordkvelle et al., 2017). In addition, an increase of precipitation can lead to higher malaria transmission due to more occasions of open, stagnant water and higher moisture (Jambou et al., 2022). More frequent hot days and greater variability in precipitation challenges for water management and agricultural stability (Berger et al., 2021; Röhrig et al., 2019), exacerbating existing vulnerabilities in already economically weak regions in northern Ghana and Nigeria, which could influence migration dynamics. However, it is not possible in this study to make

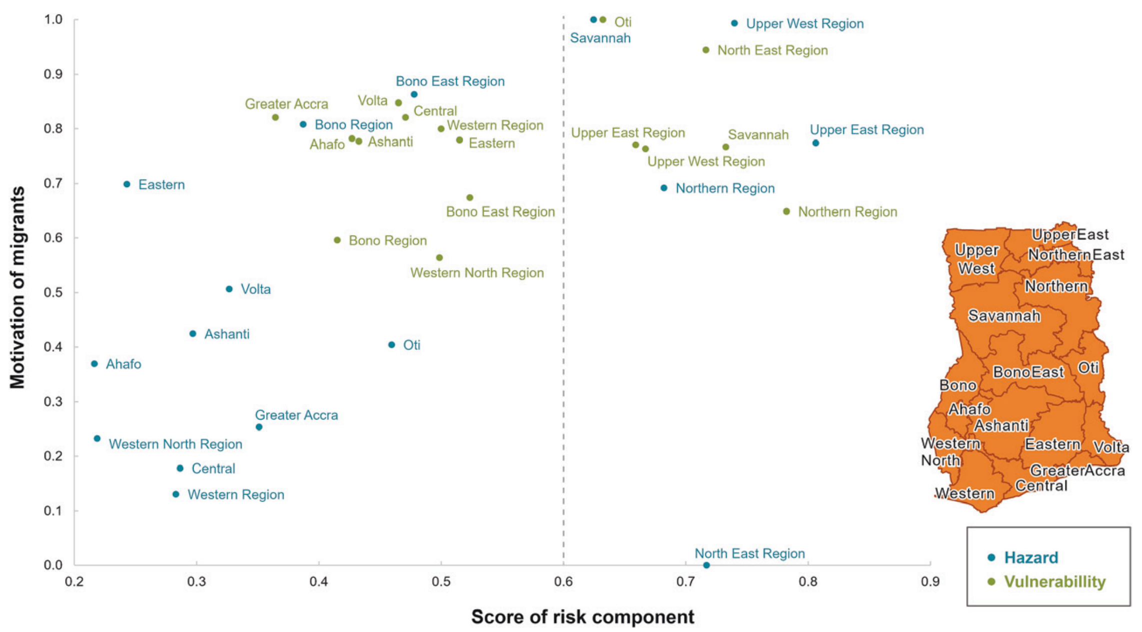

FIGURE 8
Comparison of score of risk component and the migrants' motivation for Ghana. Dashed line marks critical threshold of 0.6. Blue color = motivation related to hazard, green color = motivation related to vulnerability. A map of Ghana is included for better localization of the regions.

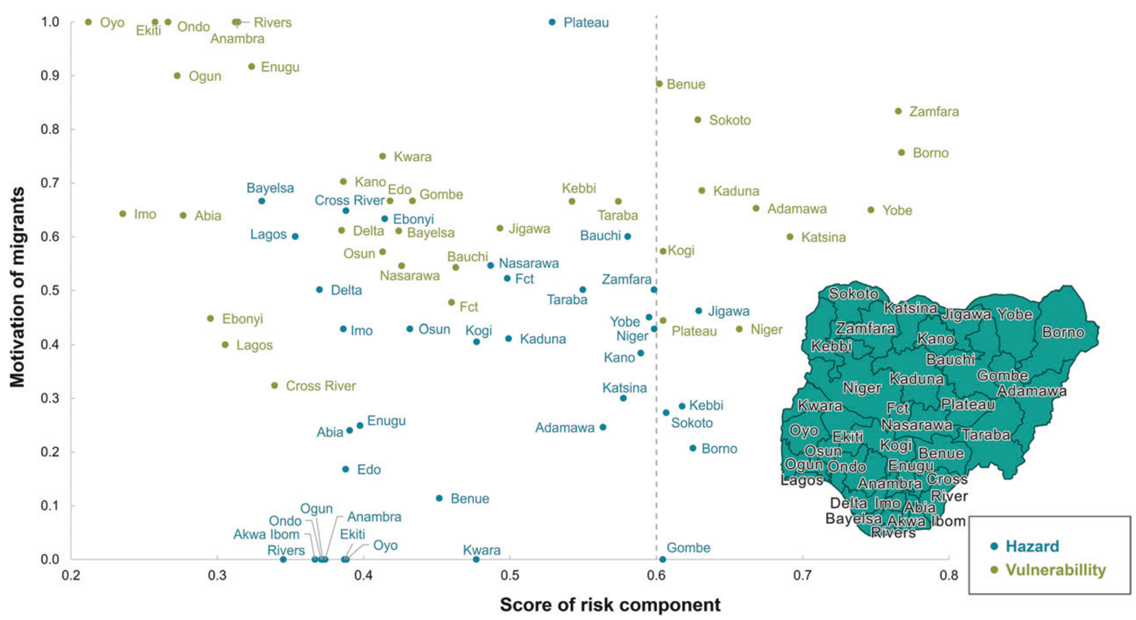

FIGURE 9
Comparison of score of risk component and the migrants' motivation for Nigeria. Dashed line marks critical threshold of 0.6. Blue color = motivation related to hazard, green color = motivation related to vulnerability. A map of Nigeria is included for better localization of the states.

any statements regarding a potential improvement or deterioration in socio-economic sensitivity or adaptive capacity in future. An improvement of the adaptive capacity or reduction of socio-economic sensitivity could lower future risk values in our assessment. Furthermore, different weightings are applied to the future components which also affect the risk score. This highlights the inherent uncertainty in predicting local migration patterns (de Valk et al., 2022).

Nonetheless, it is important to acknowledge that individual aspirations and capabilities influence migrants' decisions, shaping their responses to environmental and socio-economic factors (Adger et al., 2024; De Haas, 2021). In addition to these personal drivers, the role of government policies is also critical, as highlighted by the experts in Nigeria. Despite its potential to improve the lives of vulnerable populations, few West African governments incorporate migration into climate adaptation plans. Due to limited capacity to manage urban growth and infrastructure, policies often discourage rural-to-urban migration (Farrell, 2018; Teye and Nikoi, 2022). In order to address the challenges of rural–urban migration, policies should aim to create rural employment opportunities and reduce pressure on urban infrastructure. Actions to promote sustainable rural development and thus sustainable rural–rural and urban–rural migration should focus on agricultural resilience, land accessibility and diversification of the rural economy sector. Governments could expand sustainable agriculture programs to provide farmers with climate-smart techniques, access to credit and improved irrigation systems to reduce the current and future risks associated with climate-related hazards and socio-economic vulnerabilities.

The factors identified as highly relevant by the experts, including 'high rainfall variability', 'drought', 'dependence on agriculture', 'limited access to microcredit' in Ghana, and 'heavy rainfall' and 'conflict' in Nigeria, are also identified in recent literature as important determinants of migration decisions (Teye and Nikoi, 2022). These stressors are of particular importance in agricultural communities where livelihoods are closely intertwined with environmental conditions. For example, Rigaud et al. (2021) demonstrate that climate-induced changes, including variability in rainfall and increased drought frequency, play a direct role in migration, as these conditions lead to a reduction in agricultural output and economic instability. Additionally, heavy rainfall events and subsequent flooding have been demonstrated to displace large populations, thereby highlighting the critical role of extreme weather events in migration decisions in Nigeria (Ibrahim and Mensah, 2022; Rigaud et al., 2021).

Although environmental factors are often highlighted as drivers of migration, it is essential to recognize their interaction with pre-existing socio-economic vulnerabilities. Kaczan and Orgill-Meyer (2020) conducted a systematic review and propose that environmental factors should be regarded as contextual rather than primary drivers of migration. This is also evident in our analysis, which shows that in Ghana the reasons for environmental migration are consistent with the characteristics of the region's geography, suggesting that external factors such as environmental hazards may influence the decision to migrate. In Nigeria, by contrast, socio-economic factors appear to dominate, even in areas that are highly vulnerable to environmental hazards.

Conflicts in Nigeria not only drive rural–urban migration but also exacerbate food insecurity (Ayuba et al., 2023), which is also identified by the experts as having major influence on migration decisions in the future. In addition, financial capacity plays a crucial role in migration decisions. Research indicates that it is often wealthier households that have the means to migrate in response to climate change (Duijndam et al., 2022; Hirvonen, 2016; Kaczan and Orgill-Meyer, 2020). Limited access to microcredit, e.g., to buy necessary inputs for agricultural production on loan basis, further constrains adaptive capacities (Twumasi et al., 2020).

Regarding different population groups, rural populations, particularly farmers, are more exposed to these stressors than urban populations. This is undermined by the ongoing trend of rural–urban migration in Ghana and Nigeria (Abbass, 2012; Dick and Schraven, 2021). This migration trend is not only a response to immediate environmental stressors but also a reflection of deeper structural inequalities in access to resources and opportunities between rural and urban areas.

In addition to these structural factors, historical gender roles have influenced migration patterns in West Africa, with men more likely to migrate for employment opportunities and women more likely to migrate for family reunification or marriage. However, this trend is changing as more women are choosing to migrate independently (Setrana and Kleist, 2022). Age is also an important factor in migration decisions, with younger people generally more likely to migrate in search of better education and employment opportunities (Alarima, 2019; Ango et al., 2014). Furthermore, historical pre-colonial trade networks, ethnic ties and shared official languages continue to shape current migration cultures and cross-border migration patterns (Teye, 2022).

The presented framework integrates the aforementioned environmental factors, socio-economic conditions, and the vulnerability of exposed population groups, addressing the complex and ongoing debate about the interplay between environmental stressors and socio-economic vulnerabilities in shaping migration patterns, particularly in rural areas. This approach enables a more nuanced analysis of migration dynamics and helps identifying areas where multiple risk factors coincide.

4.2 Limitations

The study primarily focuses on external factors, such as environmental hazards, socio-economic vulnerabilities, and population exposure, with only limited consideration of individual perceptions. It does not account for personal factors such as social capital or cultural attitudes. Additionally, a more differentiated analysis of especially highly exposed demographic groups, including women and youth, could not be conducted due to the lack of data. This omission may underrepresent the social dynamics that influence migration decisions. Besides, the study focuses on rural migration because many factors, particularly those related to environmental conditions, are most relevant to rural populations dependent on agriculture. As such, migration from urban areas, which is also prevalent in Ghana and Nigeria, was not examined in detail.

The weighting process with experts introduces a certain degree of bias, reflecting the subjective judgments and potential limitations of the experts' perspectives even though expert consultation proves a higher reliability in statements than nonexperts (Han and Dunning, 2024). Such bias may influence the relative importance assigned to different indicators, potentially skewing the results toward certain vulnerabilities while underrepresenting others. Furthermore, the identification of factors and their proxy indicators have an impact on the results. However, the weights assigned mainly correspond to recent literature (see Section 4.1) and the selection of proxy indicators was restricted to the data available.

The normalization of data, required to integrate multiple datasets with varying scales, introduces an additional layer of uncertainty. Different normalization techniques, or the use of alternative quantiles to address outliers, particularly for vulnerability factors, could alter the data range and subsequently influence the overall results. Conversely, normalization facilitates interpretation and enables a wide range of data to be combined. In particular, the use of global minimum and maximum values permits the illustration of changes between the present and the future.

For the estimations of the future risk component, the study relies on climate and population projections under the RCP4.5 scenario, which can vary depending on the models and assumptions used. In particular, rainfall projections are more challenging to model accurately than, for instance, temperature data (Tomalka et al., 2021). To reduce the degree of uncertainty of the climate projections, ensemble means were employed. Although climate models predict increased rainfall in certain regions, particularly in the Sahel of Nigeria, uncertainty remains regarding the distribution of this precipitation throughout the year and its impact on rain-fed agriculture. It is also evident that the selected CMIP6 models underestimate heavy rainfall events and overestimate consecutive dry days in Ghana. Conversely, they demonstrate comparable patterns for the climate indices in Nigeria. On the other hand, the CMIP6 models seem to be able to estimate annual precipitation and extreme temperatures. Additionally, population data for Nigeria are highly uncertain, as there has not been an official population census for almost two decades.

The risk framework employed in this study is a simplified representation of the complex interactions between environmental hazards, vulnerabilities, and exposure. While simplification is necessary for modeling and analysis, it also means that certain feedback loops and dynamic interactions are not fully captured. To illustrate, the framework does not incorporate potential feedback mechanisms where increased migration could either mitigate or exacerbate local vulnerabilities, according to the context. A distinction between different types of migration may also be crucial. This is particularly true for Ghana and Nigeria, where temporal and seasonal migration is common alongside permanent migration. To identify potentially vulnerable areas, we used the responses of individuals who had already left their place of origin, without further distinguishing between different types. This could be an important consideration for more in-depth analysis. Furthermore, although adaptive capacity is included as a component of vulnerability, the framework may not fully represent the range of adaptive strategies or the potential for communities to develop new adaptive capacities in response to changing conditions.

5 Conclusion

The IPCC risk assessment framework was used in combination with spatial datasets to reflect current and potentially future migration patterns in Ghana and Nigeria, particularly for the rural, agriculture-dependent population. We have identified areas in northern Ghana and northern Nigeria in which populations are more likely to migrate due to the combined effects of high hazard, vulnerability, and exposure. Areas identified with an upward trend in risk scores reflect deteriorating livelihood conditions, which are likely to further exacerbate rural out-migration, as individuals search for ways to cope with increasing environmental and socio-economic pressures. However, due to unpredictable circumstances and individual decisions, migration might also occur in low risk areas and some people may (need to) stay in high-risk areas. In the northern regions of Ghana, there is a link between high estimated hazard scores and migrants citing environmental factors as the main reason for their migration. Whereas in Nigeria, socio-economic factors dominate, even in areas that are particularly vulnerable to environmental hazards. This suggests that the aspiration to find better employment and livelihoods is shaped by a complex range of personal and external factors, many of which are difficult to measure and not fully captured by the framework. This highlights the importance of considering the broader socio-economic context and to be more specific on exposed groups. However, it is difficult to assess the spatial distribution of, e.g., exposed women or the youth for a whole country at a local level. Additionally, projections of future climate change and related impacts remain highly uncertain, making it difficult to reliably predict future scenarios. Despite these limitations, this research contributes to a deeper understanding of how and where migration due to multiple factors might occur, providing valuable insights for policymakers seeking to develop targeted interventions that enhance local adaptive capacity and support sustainable migration pathways.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by the Directorate for Research Innovation and Development (DRID), Federal University of Technology-Minna, Nigeria and the Institutional Review Board, University of Cape Coast (UCCIRB), Ghana. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

AS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. MT: Methodology, Supervision, Writing – original draft, Writing – review & editing. JK: Methodology, Supervision, Writing – original draft, Writing – review & editing. JI: Data curation, Writing – original draft, Writing – review & editing. BN: Validation, Writing – original draft, Writing – review & editing. AO: Validation, Writing – original draft, Writing – review & editing. CC: Formal analysis, Resources, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2025.1516045/full#supplementary-material

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5 Discussion

5.1 Key findings and contributions

This dissertation is positioned at the center of current scientific debates as it draws directly on established migration theories and frameworks, demonstrating their practical application through geospatial analysis. It thus makes a substantive contribution to migration research. In other words, the three studies have shown why people migrate and where and under what conditions migration is most likely to occur, particularly among agriculture-dependent and rural populations. Through a combination of a systematic literature review and expert interviews, the most relevant factors for rural livelihoods were identified and ranked (objective 1). These factors are further addressed in Chapter 5.1.1. Based on the identification of important factors, the second objective was to map the spatial distribution of migration drivers in Burkina Faso, Nigeria, and Ghana. This was accomplished by translating the identified factors into proxy indicators and integrating them into geospatial analyses. These analyses revealed where socio-economic and environmental pressures are most pronounced (see Chapter 5.1.2). Regarding the third objective, it was demonstrated that geospatial data can play a decisive role in identifying areas of increased socio-economic and environmental vulnerability, thereby contributing to the understanding of past, present, and future migration. By combining and integrating environmental, socio-economic, and population data into different spatial analyses and visualization methods, such as thematic maps, Sankey diagrams, weighted overlays, and spatial risk assessments, it was possible to develop a more differentiated view of the factors influencing migration. The reasonability of these geospatial methods was evaluated through plausibility analyses. Particularly in Ghana, the identified susceptible regions largely aligned with reported migration rates and actual migrant motivations (Schürmann et al., 2024; 2025). For Nigeria, migrants reported socio-economic factors to be more important than environmental factors, even in regions that were identified to be prone to climatic hazards (Schürmann et al., 2025). This link demonstrates that environmental and socio-economic stressors jointly influence migration decisions. However, the relative importance of these factors varies by context. In Nigeria, for example, the effects of climate change on livelihoods may be mediated by or less perceptible than more immediate economic concerns. This suggests that migration motivations are shaped by a range of external and perceptual factors. In this context, it was shown that spatial vulnerability mapping can be a useful analytical tool. However, measuring past, present, and future migration patterns with external factors can only be carried out to a certain extent, as it does not account for subjective factors and individual decision-making processes. Additionally, it is not possible to predict whether individuals will eventually out-migrate from vulnerable areas. Nevertheless, by highlighting areas that are prone to external factors, a basis for the development of localized policies can be provided. Policy recommendations derived from these findings are discussed in Chapter 5.1.3.

5.1.1 Main factors influencing migration in the focus countries

In the past, environmental factors in areas of origin were primarily characterized by unfavorable climatic conditions, such as rainfall variability and droughts, as well as poor soil quality and land degradation (Aniah et al., 2019; Barbier et al., 2009; West and Nébié, 2019). Economic factors included limited employment opportunities and insufficient access to land (Antwi-Agyei and Nyantakyi-Frimpong, 2021; Ouedraogo et al., 2009). Conflict has also been identified as a push factor (Kamta et al., 2020; Sward, 2017). Factors such as the presence of social networks, land availability, better employment opportunities, and fertile soils were highlighted as pull factors (Dreier and Sow, 2015; van der Geest, 2011). In the context of Study 2, experts in Ghana cited consecutive dry days during the rainy season, environmental conditions for agriculture, land degradation, social networks, and job availability as the most important factors impacting current migration decisions. Although the wording of some factors in Study 3 differed slightly from those in studies 1 and 2, it is evident that the key factors remained consistent. These included climatic conditions, in particular heavy rainfall events and high rainfall variability, as well as dependence on agriculture (linked to poor economic conditions) and conflict (notably in Nigeria). These factors, along with extreme temperatures, are also expected to have a high influence on migration decisions in the future, according to the experts.

Figure 5.1 presents the factors determined in Study 1 and subsequently employed and adapted in Study 2, as well as additional factors identified in Study 3. They are embedded within a generalized conceptual framework derived and modified from the theories and frameworks described in Chapter 1.3.1. In Study 3, environmental factors are categorized as hazard, socio-economic factors as vulnerability, and population distribution as exposure. For all factors represented by a box with a continuous line, corresponding proxy indicators were identified and integrated into spatial assessments within studies 2 and 3 (see also Chapter 4.2, Table 1, and Chapter 4.3, Table 1). The component "exposure" was only considered in Study 3. This conceptual framework underscores that the dissertation primarily focused on external, measurable factors derived from spatially and locally available data. The main outcome was the identification of areas where climatic and environmental factors interact with socio-economic vulnerabilities, which could lead to the degradation of livelihoods (Chapter 5.1.2). Individual aspirations, capacities, and decision-making processes related to leaving these degraded areas or not, represented by gray elements in Figure 5.1, could not be addressed in this dissertation, due to data limitations.

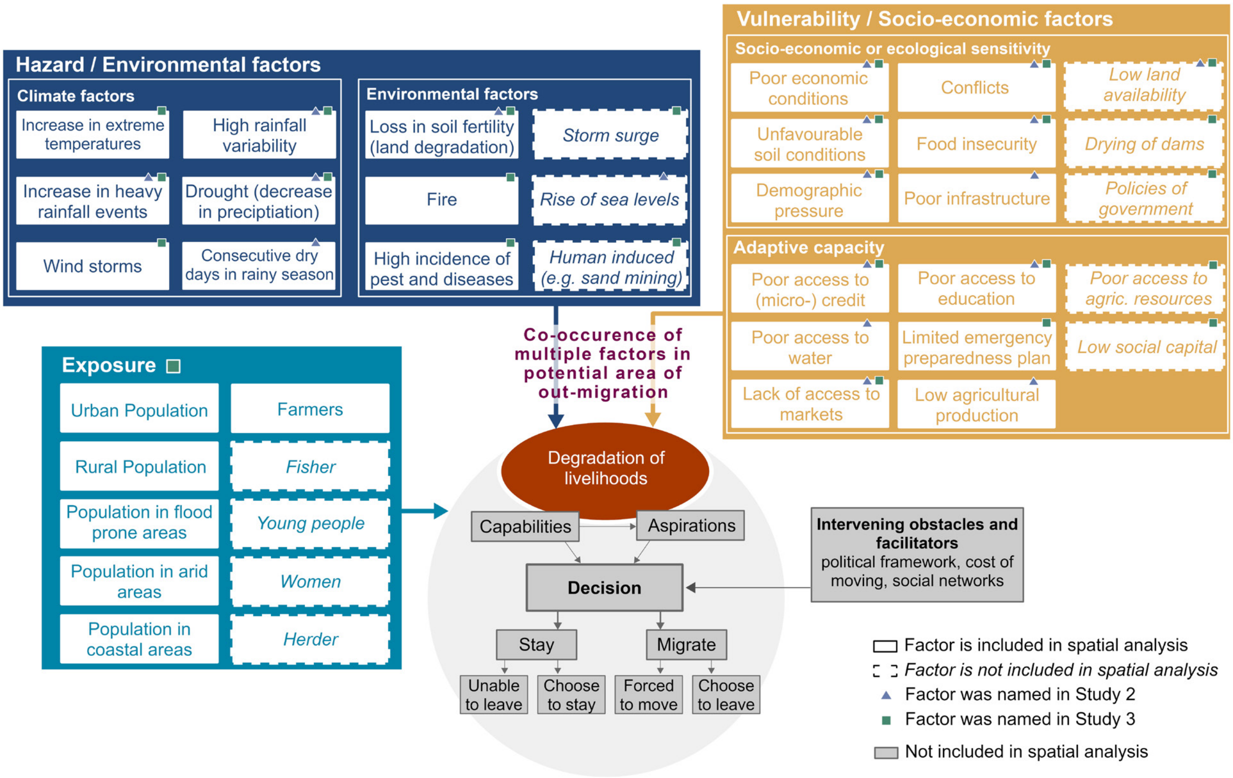

Figure 5.1 *Conceptual framework of factors influencing migration and their inclusion in spatial analysis. It illustrates which factors could be included in the spatial analysis based on data availability and accessibility. The concept builds on a structure modified from the IPCC risk framework (IPCC, 2014) with aspects of the Foresight framework (Foresight, 2011), the push-pull theory (Lee, 1966), and the aspirations–capabilities framework (de Haas, 2021). Agric. = agricultural.*

5.1.2 Past, current, and future areas with high likelihood of migration

The areas identified as the most vulnerable, i.e., with a higher likelihood of out-migration across the past, the present, and the future, are presented in the following. Figure 5.2a shows areas (at administrative level 2) identified as particularly vulnerable to environmental factors, socio-economic factors, or both across the three studies. As projections of future socio-economic factors were only possible to a limited extent, the description of future developments is primarily based on projected changes in climate. Figure 5.2b shows the projected changes in various climate indices in the near future that could influence future climate-induced migration patterns. While migrants may not explicitly identify climate change as the main factor behind their decision to move, environmental stressors, such as land degradation and irregular rainfall, often translate into economic challenges such as declining agricultural productivity (Borderon et al., 2019). These are typically perceived as reduced income, food insecurity, and deteriorating livelihoods. Overall, it is difficult to isolate the effects of climate change from other socio-economic factors, as climate-induced migration in the region is deeply rooted in historical patterns and inequalities (Jarawura et al., 2024). In this context, it is important to recognize that climate change is not a distant or future threat but is already transforming livelihoods and landscapes. The global average temperature will likely exceed 1.5°C by the early 2030s (IPCC, 2021b). This threshold should not be considered a tipping point between safety and danger. Climate change is already causing severe impacts, especially in vulnerable regions such as West Africa (IPCC, 2022; 2023), exacerbating existing pressures and contributing to mobility in complex ways. This dissertation does not attempt to quantify the number of individuals who migrate directly as a result of specific environmental events, such as floods or droughts, nor does it focus on singular events. In addition, the identification of vulnerable areas can only show the potential migration, assuming a higher likelihood of migration due to harsher circumstances (higher vulnerability) than in comparable areas in Burkina Faso, Ghana, and Nigeria.

In the Sudan-Sahel region, severe droughts in the 1970s and 1980s led to large-scale migration from drought-affected areas to more favorable regions (Mertz et al., 2012; Schraven et al., 2020), as shown in Study 1 by case studies from Burkina Faso, where ethnic groups such as the Mossi and Fulani moved southwards (Barbier et al., 2009; Jahel et al., 2018). In addition, historical land degradation in the north of Burkina Faso has resulted in migration to more fertile southern regions, leading to land use changes and environmental pressures in destination areas (West and Nébié, 2019). For Burkina Faso, vulnerable areas and thus migration patterns were not estimated through spatial analysis in this dissertation due to data gaps. However, the areas of origin identified in Study 1, such as the regions Sahel and Nord (see Figure 5.2a), align with current census data that classify these regions as having high out-migration rates (INSD, 2020). By contrast, regions such as Centre (which encompasses the capital city of Ouagadougou) and Hauts-Bassins (where the second-largest city, Bobo-Dioulasso, is located) are currently among the primary destinations for internal migrants. The western Sahel zone, including northern Burkina Faso, is experiencing rising levels of violence and conflict between pastoralists and farmers, exacerbated by changing rainfall patterns and competition for natural resources (Larémont, 2021). Since 2016, Burkina Faso has also faced terrorist attacks, which have reduced agricultural productivity and pressured many farmers to shift from cereal to cash crops (Kafando and Sakurai, 2025). Disruptions related to conflict led to a 40-50% decline in food trade activities, exacerbating food insecurity (Béné et al., 2024). While some areas of Burkina Faso have experienced increased annual rainfall since the drought of the 1980s, improvements in agricultural conditions have been limited and unevenly distributed (Porkka et al., 2021). Future climate projections and associated changes in climate indices (see Figure 5.2b) show a widespread increase in extreme heat days across the country, accompanied by an increase in consecutive dry days in certain regions and more frequent heavy rainfall events in northern areas. Meanwhile, recent research suggests that rainfall may increase in parts of Burkina Faso, especially in the north (see Figure 5.2b), but projections are highly uncertain (Berger et al., 2021; Röhrig et al., 2021). Due to the importance of soil moisture and other parameters, it is difficult to predict the impacts of climate change on agriculture. In addition, higher temperatures are expected to raise evapotranspiration rates, which will further complicate the outlook for agricultural production (Sawadogo et al., 2024).

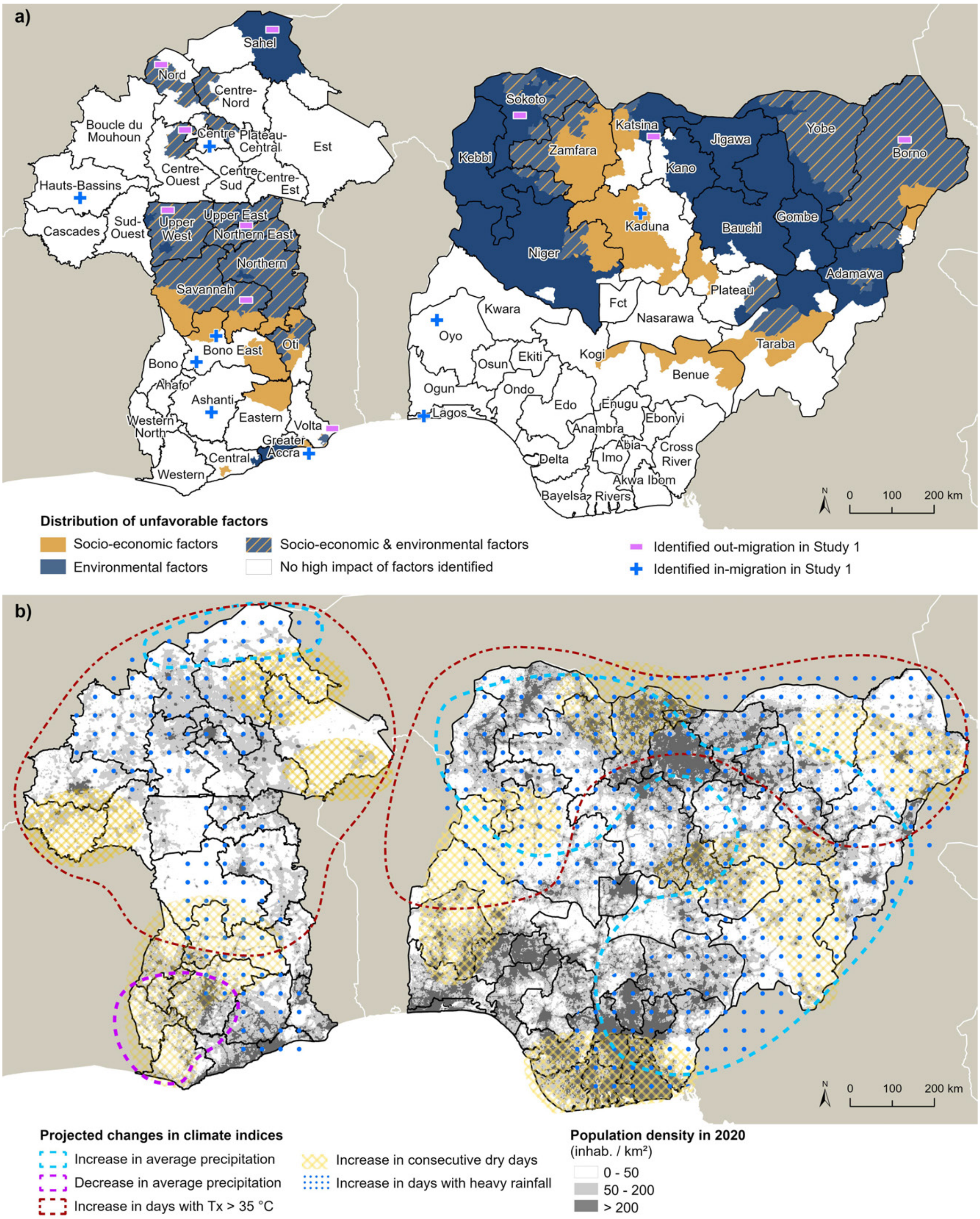

Figure 5.2 *Visual synthesis of studies 1, 2, and 3.* ***a)*** *Vulnerable areas, and thus higher likelihood of migration, in Burkina Faso, Nigeria, and Ghana, due to unfavorable environmental and socio-economic factors identified for the past and present. These areas were either reported as migration origins in Study 1, had at least a medium-high impact of factors in Study 2, or the impact scores were at least 0.5 in the present risk assessment in Study 3.* ***b)*** *Projected future changes in climate indices. Indices for Burkina Faso (2021-2040, baseline 1994-2015) originate from the IPCC atlas (Gutiérrez et al., 2023). Maximum 1-day precipitation was used to display heavy rainfall events. For Nigeria and Ghana, indices (2021-2050, baseline 1994-2015) are based on own calculations conducted in Study 3. Population data is based on Wang et al. (2022). Tx = maximum temperature.*

In Nigeria, only a limited number of studies could be included in the analysis of historical migration patterns. Although these few studies cannot represent the entire country, they indicate a general migration trend from northern states to southern or nearby safer states, often in response to conflict and resource scarcity. Flooding caused by heavy rainfall events has historically and recently led to both temporary and permanent displacement, as seen in the flooding events of 2012 and 2022 (IFRC, 2023; Zickgraf et al., 2016). Moreover, the areas of origin identified in Study 1 largely coincide with the regions identified as vulnerable in the spatial analysis in the risk assessment in Study 3. The states identified as particularly vulnerable are located in northern Nigeria (including Kano, Katsina, Borno, Yobe, and Sokoto states; Figure 5.2a). These states are characterized by poor access to markets and education, or dependence on agriculture (Schürmann et al., 2025). In addition, these states are experiencing declining rainfall and land degradation, which is exacerbating food insecurity (Kamta et al., 2020; Nwilo et al., 2020). Environmental degradation has caused herders to migrate southward, leading to conflicts with farmers in central and southern Nigeria (Kamta et al., 2020; Lenshie et al., 2021). This migration, in turn, contributes to further land degradation in destination areas through urban expansion and increased pressure on resources (Aweda et al., 2024). Projected climate conditions (Figure 5.2b) suggest an increase in extreme heat days, consecutive dry days, and heavy rainfall in northern parts of Nigeria, extending to certain central parts of the country. The spatial overlap between future shifts in climate indices and population density illustrates the risks of climate change in traditional source and destination areas of migration. As illustrated in Study 3 (Figure 5.2b), parts of northern Nigeria may experience increases in precipitation. However, precipitation variability (also expressed through heavy rainfall events) and high evapotranspiration rates might limit the potential for agricultural productivity (Sawadogo et al., 2024; Schewe and Levermann, 2022). As observed in Study 3, socio-economic factors are primarily cited as influencing migration decisions. Migrants often do not attribute their movement to environmental reasons, even when living in hazard-prone areas. Although climate or environmental change is rarely cited directly as a driver of migration, it has an indirect impact through its effects on agriculture and can reduce the income of farmers (Amare and Balana, 2023). This suggests that environmental factors interact with existing socio-economic vulnerabilities and should be understood as contextual rather than primary drivers of migration.

In Ghana, historical migration has largely followed a north-to-south trajectory (van der Geest, 2011), this is also evident from Study 1, which showed that people mainly migrated from regions such as Upper East, Upper West, and Northern (Figure 5.2a), because they were characterized by low agricultural productivity, land degradation, and erratic rainfall patterns. The spatial vulnerability assessments reinforce this picture by showing that the population in the northern regions is most affected by the combined occurrence of adverse economic and environmental conditions, resulting in a high likelihood of out-migration (see Figure 5.2a). These patterns remain evident in recent census data, which show negative net migration rates in northern Ghana between 2010 and 2020. However, regional patterns of migration do not always align with levels of environmental or socio-economic vulnerability (Chapter 4.2, Figure 6). The Eastern Region had a relatively high negative net migration rate (out-migration) despite only a small proportion of its rural population being exposed to adverse conditions. On the other hand, regions such as Western, Bono East, and in particular, Greater Accra, experience socio-environmental vulnerability but have a positive net migration rate. Even though it is moderately affected by environmental risks and a high proportion of the population resides in vulnerable areas, the Greater Accra Region is a major destination for internal migrants (GSS, 2023; Schürmann et al., 2024). The rural-urban migration pattern will likely continue, potentially accelerating urbanization in primary (e.g. Accra or Kumasi) and secondary cities (e.g. Takoradi) (Asabere et al., 2020; Korah et al., 2025; Toure et al., 2020). The ongoing popularity of urban areas, despite their own vulnerabilities (see Chapter 1.2), suggests that migration decisions are influenced by perceived opportunities, personal aspirations, and social networks. Future climate projections (Figure 5.2b) suggest that these southern or centrally located regions may experience an increasing frequency of heavy rainfall events, consecutive dry days, and less average precipitation, potentially altering local environmental conditions, which could pressure host communities.

5.1.3 Implications of current and future migration patterns for policymaking

Migration can contribute to enhance the socio-economic well-being of migrants and their families (Gemenne and Blocher, 2017). Moreover, social and financial remittances can play a crucial role in improving the long-term resilience of rural livelihoods (Scheffran et al., 2012). Rather than viewing migration solely as a challenge to be reduced, its positive aspects should be recognized, such as its role in adapting to environmental or economic challenges. However, to improve livelihoods and ensure that migration is a choice rather than a necessity, recommendations should take into account the broader structural factors that influence migration dynamics. Therefore, involving different sectors in policymaking, namely agriculture, development, climate or environment, economy and employment, as well as migration and urbanization, is important (Schraven et al., 2020). Thus, this chapter discusses a collection of (policy) recommendations from the current literature that could be adopted to reduce vulnerability in the identified areas (see Figure 5.2a), thereby highlighting the dissertation's contribution to localized policy recommendations.

In order to improve agricultural production in northern Burkina Faso, Barbier et al. (2009) suggest that irrigation of vegetables could help farmers to invest in other sectors, as it is less dependent on climatic conditions. Additionally, small-scale irrigation has become a common dry-season strategy, offering farmers an alternative to migration by reducing their vulnerability. Addressing farmers' access to credit and securing land ownership will help them adopt sustainable agricultural practices more easily and be resilient to climate change (Maré et al., 2022; Noufé, 2023). According to Gansonré (2021), the promotion of the rural non-farm economy through minimum wage schemes and access to rural financial services could improve welfare in the semi-arid areas of Burkina Faso.

States in northern Nigeria, such as Niger, Katsina, Jigawa, Yobe, Borno, and Gombe, should consider revising land use regulations, encouraging sustainable agricultural practices, investing in rural infrastructure, addressing specific regional conflicts, and enhancing household resilience. These actions are essential for tackling challenges like food security (Okeleye et al., 2023; Olanrewaju and Balana, 2023; Yahaya et al., 2024). Market participation through public infrastructure investments, particularly in cowpea production, has demonstrated positive effects on household food security and income in the identified vulnerable areas in northern Nigeria (including Borno, Gombe, Jigawa, Kaduna, Katsina, Kebbi, Sokoto, and Zamfara) (Manda et al., 2020). In general, addressing infrastructure deficiencies and promoting education are crucial for developing effective food security strategies (Okpala et al., 2023).

In northern Ghana (Northern, Upper East, and Upper West regions), the adoption of multiple sustainable agricultural practices, including improved seeds, fertilizer, and soil and water conservation, has shown greater positive impacts on farm income and food security compared to single practices (Setsoafia et al., 2022). Policymakers should improve farmers' access to credit, markets, and off-farm income opportunities to enhance agriculture in the Upper East Region. They should also promote farmer-to-farmer extension services (farmer-to-farmer knowledge exchange) and support the integration of traditional practices with climate-smart agriculture (Boansi et al., 2023). Yenglier Yiridomoh and Owusu (2022) identified farmer-based organizations, climate information use, and access to financing as key factors in shaping the responses of women farmers to climate extremes in the Upper West Region. Additionally, local economic development policies play a crucial role in poverty reduction, particularly through local business creation in the Northern, Upper East, and Upper West Regions (Tackie et al., 2022).

Rapid urbanization in Ghana and Nigeria is causing land use changes and environmental impacts in major metropolitan regions such as Accra, Kumasi, and Lagos (Asabere et al., 2020; Ekoh et al., 2022; Obi-Ani and Isiani, 2020). This trend is expected to continue, as more than half of Ghanaians and Nigerians now live in urban areas (Anarfi et al., 2022; World Bank, 2025). While rural-urban migration is driving urbanization, this is not adequately addressed in Ghana's national urban policy (Kutor et al., 2025). The rapid urbanization has implications regarding (un-)sustainability, including reduced economic opportunities, social segregation, and the loss of vegetated areas (Anarfi et al., 2022). To address urban sprawl in Ghanaian and Nigerian cities, some strategies from countries in the global north could be used, such as densifying already highly urbanized areas and preserving farmland in rapidly urbanizing rural districts (Amponsah et al., 2022). However, successful implementation of such strategies will require addressing land tenure conflicts, strengthening planning institutions, and improving cooperation among urban authorities (Amponsah et al., 2022). In general, the construction of roads, schools, and other infrastructure is beneficial to rural and urban areas, but rural development should not be seen as a way to keep people in rural areas (Beauchemin and Schoumaker, 2005; Black et al., 2022).

Strengthening local adaptive capacity and resilience can increase people's ability to decide for themselves if and when they want to migrate and thus reduce the need for distress migration. However, local efforts alone cannot address the full range of migration drivers and preferences. To improve outcomes, they should be complemented by measures that support adaptive and planned forms of mobility (Lindegaard et al., 2024). According to Gemenne and Blocher (2016), policies should aim to assist and protect migrants and non-migrants affected by environmental changes and provide alternatives to migration for those who wish to stay in their communities.

Climate vulnerabilities can be reproduced in migration destinations, as described for southern Ghana (see Chapter 5.2), potentially making it an unsustainable adaptation strategy for marginalized groups (Vinke et al., 2020). In addition, migrants often face further difficulties, such as the loss of critical support systems and experiences of discrimination. Also, other unfavorable conditions could be found in the destination area, like food insecurity and limited access to land (Armah et al., 2025; Sward, 2017). These compounding vulnerabilities underscore the fact that, while migration may be a proactive livelihood strategy for some, it does not uniformly lead to improved livelihoods. It is therefore imperative that policymakers intensify their efforts to create safe migration pathways for people who are affected by climate change (Baada et al., 2023).

5.2 Discussion of the methodological approach

5.2.1 Theories and frameworks applied

A key distinction among the studies is how factors influencing migration were structured and assessed. The theoretical background of Study 1 draws on the push-pull theory, which has long been a fundamental theory in migration research (Beverelli, 2022; Czaika and Kis-Katos, 2009; Laajimi and Le Gallo, 2022). In addition, elements of the Foresight framework were applied to categorize migration drivers. In this study, factors influencing past migration were derived from existing case studies in which migrants were interviewed directly. As discussed in Chapter 1.3.1, the push-pull theory and the Foresight framework provide a simple categorization of drivers and factors of migration that is helpful for their initial identification and mapping. In addition, the juxtaposition of push and pull factors of the relevant drivers shows that they are closely linked, but that a push factor does not directly have a corresponding pull factor. On the other hand, the migration process is oversimplified, and the social or cultural dimension of migration, among other aspects, is underestimated. While the push-pull theory is still used in migration research, there is an ongoing debate about its ability to capture the complex nature of migration. Thus, recent studies propose more nuanced approaches to understanding migration decisions (de Haas, 2021; Sherbinin et al., 2022; van Hear et al., 2018). In response to that, local experts contributed with contextual knowledge on the importance of the identified factors. Although Study 2 does not apply a specific theoretical framework directly, the relevance of existing theories, like the aspirations-capabilities framework, is acknowledged and discussed. In Study 3, the IPCC risk framework was adopted, which focuses on climate-related risks, socio-economic vulnerability, and exposure. These components can largely be measured using geospatial proxies. Applied to migration, this concept highlights migration as a potential adaptation strategy to climate risks (McLeman et al., 2021). As discussed in Chapter 1.2, migration can reduce exposure, redistribute resources, and increase resilience. Although the framework effectively captures structural sources of risk, it does not consider individual motivations. Both external conditions and personal circumstances influence aspirations for a better livelihood, the latter of which are difficult to measure and are not usually spatially explicit. Rather than attempting to predict exact migration flows, Study 3 explores potential future migration patterns under different environmental and socio-economic conditions. This exploratory approach allows a more informed understanding of potential future developments without making deterministic predictions.

Overall, the applied theories and frameworks provided complementary perspectives for analyzing migration across different time periods. The push-pull theory and Foresight framework helped identify past and present migration drivers. The IPCC risk framework facilitated the interpretation of current challenges and potential future circumstances. However, some elements, like individual aspirations and decision-making (see Figure 5.1), could not be captured through geospatial data. As such, the frameworks were applicable only to the extent that conditions could be spatially measured, such as livelihood degradation.

5.2.2 Reflection on methodological strengths and limitations

This dissertation employs a mixed-methods approach, which has its strengths and limitations. These are contrasted for each method in Table 5.1, with a more detailed reflection provided thereafter.

Table 5.1 *Overview of main strengths and limitations of applied methods.*

Applied method	Strength	Limitation
Literature review	The theoretical background was provided for different study areas by various authors (including multiple viewpoints on migration), and key migration drivers and factors were identified.	The choice of literature may influence the findings, introducing potential for selection bias. It may not capture the most recent or region-specific developments due to publication gaps, for example, there were few case studies for Nigeria. In addition, the authors applied different methods in their case studies that may limit comparability.
Expert interviews	Expert interviews allowed for context-specific weighting of factors influencing migration, improving the relevance and applicability of results to local conditions.	The limited number of experts may have introduced bias, with opinions potentially influenced by affiliation or personal experience.
Collection of spatial data and development of proxy indicators	The use of proxy-indicators facilitated large-scale, measurable spatial analysis of the external factors driving migration and supported the identification of vulnerable areas.	Proxy indicators may oversimplify or misrepresent complex realities (Birkmann et al., 2022). Spatially explicit data on social factors were limited, and projections on socio-economic data were lacking.
Data integration and spatial analyses	Combination of multiple data types to provide a more holistic, nationwide, and spatially explicit understanding of migration drivers and patterns. Harmonization of data ensured comparability across regions.	Aggregation and normalization methods may have impacted and altered actual values. The integration of diverse datasets poses methodological challenges and may introduce uncertainties.
Data visualization	Supported the interpretation of overlapping vulnerabilities and likelihoods of out-migration. Visual representation is more attractive than numbers and statistics to communicate findings to policymakers.	Visual representations may oversimplify complex interactions and are influenced by the underlying data, normalization, and integration methods.
Plausibility analysis	Comparative analyses of net migration rates (for Ghana) and migrant surveys with impact and risk maps provided information on the reliability of the results and gave insights on the level of interpretation.	Comparing the outcome with net migration rates offered limited verification because a person can live in a vulnerable area but decide not to migrate, or vice versa. Net migration rates were only available for Ghana.

The results show that integrating spatial data with expert knowledge and established migration frameworks can be used to map vulnerable areas and thus assess areas with a higher likelihood of rural out-migration. However, the reliance on the opinions of a few experts is a possible source of bias. Nevertheless, this approach enabled the systematic ranking and weighting of the factors influencing migration, ensuring local relevance. In addition, as Krueger et al. (2012) noted, the number of experts involved does not determine the quality of environmental modeling, but by the quality of inquiry and the integration of diverse viewpoints.

Moreover, spatially explicit data on social factors, e.g. social networks or household characteristics, were lacking. People's perceptions of the environmental, political, economic, and social surroundings, along with their personal values, norms, aspirations, and expectations, strongly influence their intention to migrate (Adger et al., 2024; de Haas, 2021). These factors were also ranked as important in the expert interviews. It was also not possible to determine who would eventually migrate and whether migration would be temporary or permanent. Collecting such data would have required large-scale migrant surveys, which was beyond the scope of this dissertation. The lack of spatially explicit data on social interactions is common in spatial analyses of social-ecological systems (Cobb et al., 2024; Helbling et al., 2023). The assessment of future developments was based on climate and population data, as future socio-economic data could not be integrated due to data limitations. Future climate indices were generated using the delta method (Hay et al., 2000), which adds the difference between future and historical model data to observed baselines. While this approach assumes that the future will evolve in continuity with the past, it introduces a degree of uncertainty. However, it is a well-established method in scenario-based research and allows for plausible and interpretable future developments (Jimenez et al., 2024). Yet, climate projections themselves are also uncertain and can vary across models. To address this, ensemble means were calculated, combining multiple models to reduce biases and improve the overall reliability of climate-related results (Ajibola et al., 2022; Bobde et al., 2024).

A recurring finding in all three studies is the identification of northern regions in Burkina Faso, Nigeria, and Ghana as zones of vulnerability and potential out-migration (see Figure 5.2). While this is consistent with broader literature, it may also be influenced by the methodological design, in particular the normalization process of data used in Study 3. Because data of each country were normalized independently, it is possible that the drier north of Nigeria and the slightly wetter north of Ghana may end up with similar normalized values despite differences in their actual environmental conditions.

While this study focuses on identifying areas facing multiple, co-occurring stressors, which may be areas where migration is more likely to occur, it does not consider feedback loops. For example, it does not analyze how migration itself might affect the vulnerability of the areas left behind. Analyzing these feedbacks would require a different methodological approach, such as agent-based modelling (Kniveton et al., 2011; Nelson et al., 2020).

6 Future research

The research design and methods employed in the three studies are adaptable to other countries or regions in West Africa with similar datasets, particularly those in the Sahel zone, where environmental stress and socio-economic fragility overlap and field work might be risky due to security issues (like Niger or Mali). Similarly, it could be applied to map socio-economic and environmental vulnerabilities in other rural, agricultural dependent countries in different parts of the world, like Central America. There, smallholder communities practicing rain-fed agriculture are facing the impacts of climate change, including increased crop failures and reduced income opportunities, which could lead to out-migration (Donatti et al., 2019; Huber et al., 2023).

Future studies could build on the presented spatial approach by incorporating more comprehensive social data, including risk perceptions and household decision-making. Further validation of the results could be achieved by involving local communities and their perceptions on the mapped hazards and vulnerabilities. Participatory mapping and locally collected geospatial data can complement remote sensing observations to provide valuable insights into land use changes, community assets, population movements, and environmental impacts (Kleemann et al., 2017; Kouassi et al., 2021; Okotto-Okotto et al., 2021). However, such data collection would likely be limited to small-scale studies and accessible, relatively safe areas. This would limit the generalizability of the results and make broader spatial integration difficult.

Although progress has been made in mapping and visualizing past and potential migration patterns, gaps remain in understanding how populations will respond to future climate change and socio-economic pressures. As a result, improved analyses of socio-economic impacts and climate change projections are needed (Fitzpatrick et al., 2020). Schewel et al. (2024) have pointed out that improvements in data collection are critical to enhance the accuracy of predictive models, especially in climate-vulnerable areas such as sub-Saharan Africa. This includes establishing reliable, long-term monitoring frameworks as well as increasing the temporal frequency and spatial resolution of migration and climate data. Furthermore, as suggested by Beyer et al. (2023), future research should broaden its scope beyond the traditional emphasis on temperature and precipitation. The use of model-based reconstructions from projects such as the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) provides an opportunity to reconstruct historical baselines and simulate future risks more accurately.

In light of the dissertation's emphasis on mapping areas of origin, a logical subsequent step would be a more detailed identification of potential destination areas. As demonstrated in Study 1 through the use of Sankey diagrams, this cannot be accomplished by merely reversing the findings from the areas of origin, as the push and pull factors are not reciprocal. The analysis of destination areas would require a distinct approach that considers various factors, including economic opportunities, social networks, access to services, and the adaptability of the region. It is necessary to identify what makes a place attractive to migrants, and conducting surveys among migrants would be beneficial in this context. In addition, including structural indicators in the spatial analysis would help assess the resilience and hosting capacity of potential destination areas (Szaboova et al., 2023). Particular attention should also be paid to the urban dimension of rural out-migration. Addressing urban vulnerability requires distinct analytical frameworks and data because urban migration dynamics are shaped by economic, infrastructural, and social factors in addition to climate stressors (Adger et al., 2021). Informal settlements, urban poverty, and exposure to extreme climate conditions create vulnerable landscapes different from those in rural areas. Another possible direction for future studies is to investigate how local adaptation strategies, such as crop diversification, small-scale irrigation, and engagement in off-farm livelihoods (described in 5.1.3), mediate migration decisions. These strategies may reduce the need for migration in some contexts, but in others, they could increase mobility by expanding economic possibilities (Hoffmann et al., 2022). In general, migration should not be seen as a last resort or response to a certain risk, but also as a proactive and potentially positive livelihood strategy, as pointed out in Chapter 1.2.

The results of the three studies will be disseminated to relevant stakeholders within the MIGRAWARE network. However, they also have the potential to be communicated to local or international governments, as migration in the context of climate change is receiving increasing attention in global policies, including the achievement of the SDGs. Poor infrastructure leaves communities vulnerable to the impacts of extreme weather, hindering poverty reduction and overall well-being (Codjoe and Atiglo, 2020). Aligning adaptation strategies with the SDGs and integrating resilience into national policies can mitigate these impacts and promote sustainable development (Baarsch et al., 2020; Codjoe and Atiglo, 2020). Vulnerability mapping, as conducted in this dissertation, provides the necessary geographic details to localize development measures. Many SDGs, especially those targeting poverty (SDG 1), hunger (SDG 2), and climate action (SDG 13), require context-specific strategies. Stakeholders could use the spatial data produced within the studies to identify areas of high vulnerability and low adaptive capacity, helping to translate global goals into locally applicable interventions. For example, identifying vulnerable, agriculturally dependent areas can help guide food security and rural development programs. The identification of regional and intraregional inequalities could also contribute to SDG 10 ("Reduced inequalities") and form a basis for future development strategies that are more equitable.

7 Conclusion

This dissertation demonstrated that using a mixed-method approach, involving expert knowledge and spatial analysis, enabled the mapping of regions where multiple unfavorable environmental and socio-economic factors intersect, particularly in rural, agriculture-dependent contexts in Burkina Faso, Nigeria, and Ghana. This enabled the identification of areas with a higher likelihood of migration. Evidence was found that a push factor in the area of origin does not automatically define the pull factor in the destination area. Generating spatial overlaps was an essential contribution to visualizing the spatial interconnectedness of environmental hazards and socio-economic vulnerabilities, highlighting vulnerable areas in northern Nigeria and Burkina Faso, as well as in coastal and northern Ghana. These results, in combination with plausibility analyses, suggest that migration often results from the combined and context-specific interaction of multiple factors.

While socio-economic reasons are most often cited to influence migration, environmental-related stressors, such as rainfall variability, flooding, and extreme heat, can indirectly contribute to migration by negatively affecting agricultural income and food security. In general, migration is complex and a personal decision that is shaped by a combination of structural and personal factors, but it is challenging to disentangle their individual effects on migration. Furthermore, future migration patterns are difficult to predict due to uncertainties in climatic, economic, and political developments. Nevertheless, climate data have proven useful in estimating regions where agriculture and rural livelihoods will likely become increasingly vulnerable. The applied theoretical frameworks provided different perspectives on past, present, and potential future spatial patterns of migration. However, when integrated with spatial data, these frameworks have limited ability to account for the more subjective aspects of migration that determine whether and when individuals will eventually migrate.

Despite this limitation, the dissertation makes an essential contribution to migration research by identifying the most important factors influencing migration, mapping these factors spatially, and overlaying them to determine vulnerable areas using multiple geospatial approaches. Furthermore, the importance of incorporating both spatially measurable factors and personal aspirations in future studies is emphasized. Thus, this dissertation provides a better understanding of past, present, and future migration patterns in West Africa, as well as a replicable and transferable methodology.

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Eidesstattliche Erklärung / *Declaration under Oath*

Ich erkläre an Eides statt, dass ich die Arbeit selbstständig und ohne fremde Hilfe verfasst, keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt und die den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

I declare under penalty of perjury that this thesis is my own work entirely and has been written without any help from other people. I used only the sources mentioned and included all the citations correctly both in word or content.

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