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Agricultural livelihoods, adaptation, and environmental migration in sub-Saharan drylands: a meta-analytical review

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Agricultural livelihoods, adaptation, and environmental migration
in sub-Saharan drylands: a meta-analytical reviewRoman Hoffmann^{1,2,3,*} , Charlotte Wiederkehr⁴ , Anna Dimitrova⁵ and Kathleen Hermans^{4,6} ¹ International Institute for Applied Systems Analysis (IIASA), Wittgenstein Centre for Demography and Global Human Capital (IIASA, OeAW, University of Vienna), Laxenburg, Austria² Vienna Institute of Demography (OeAW), Wittgenstein Centre for Demography and Global Human Capital (IIASA, OeAW, University of Vienna), Vienna, Austria³ Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany⁴ Computational Landscape Ecology Department, Helmholtz Centre for Environmental Research (UFZ), Leipzig, Germany⁵ Department of Climate, Atmospheric Science, and Physical Oceanography at the University of California, San Diego, CA, United States of America⁶ Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Halle, Germany

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E-mail: hoffmannr@iiasa.ac.at**Keywords:** climate change, migration, adaptation, drylands, sub-Saharan Africa, systematic review, meta-analysisSupplementary material for this article is available [online](#)**Abstract**

Drylands in sub-Saharan Africa are strongly affected by the impacts of climate change. Temperature increases, changes in rainfall patterns, and land degradation pose serious threats to food security, health, and water availability in the region. The increase in livelihood insecurity can in turn trigger migration as a way to adapt or cope with stress. Based on 89 original case studies, this study uses review and meta-analytical techniques to systematically explore the relationship between environmental change, adaptation, and migration in rural areas in sub-Saharan drylands. We show that households use a diverse range of strategies to respond to environmental hardships in different livelihood and ecological contexts. While migration is common in some communities, it is of less relevance to others, and it can take various forms. Our findings indicate that migration is often used as a complementary strategy to other forms of adaptation, which can vary depending on situational needs. We use cluster analysis to identify adaptation clusters and show how linked response strategies differ by socioeconomic conditions. We find that migration can serve as a last resort measure for highly vulnerable groups, or be used in combination with *in-situ* strategies for diversifying income and adapting agricultural practices. Our results have important implications highlighting the role of local conditions and complementary forms of coping and adaptation for understanding environmental migration.

1. Introduction

Drylands cover about 46.2% of the global terrestrial area and are home to over 2 billion people or around one third of the global population (IPCC 2019, Hoover *et al* 2020). They are ecosystems characterized by high temporal and spatial rainfall variability and aridity (FAO 2019). Climate change is expected to have major impacts on these areas with increasing levels of water stress, desertification, land degradation, and a continued loss of biodiversity. By the end of this century, drylands are projected to further

expand by 11% under a medium (RCP4.5) and up to 23% under a high (RCP8.5) greenhouse gas emission scenario relative to a 1961–1990 baseline (Huang *et al* 2016).

In sub-Saharan Africa (SSA), drylands represent an important ecosystem accounting for 70% of the total cropland (Cervigni and Morris 2016). The region is highly exposed to climate change impacts, which come in form of slow-onset processes combined with the simultaneously increasing frequency and intensity of extreme events such as floods and droughts (IPCC 2018).

With a high share of its population depending on agriculture, high levels of poverty, and low adaptive capacities, the region is characterized by a high vulnerability (Hoffmann 2022, IPCC *et al* 2022). Climate change is expected to further contribute to this vulnerability by exacerbating existing development challenges and non-climatic stressors, such as conflicts (FAO 2018). With worsening climate impacts, limits may be reached beyond which adaptation becomes impossible as communities lack means and resources to adequately prepare against and tolerate hazards (Warner *et al* 2012, Dow *et al* 2013, Xu *et al* 2020).

Under these circumstances, migration can represent a suitable strategy to cope with and adapt to the climate impacts (Foresight 2011, IPCC *et al* 2022). By having household members or relatives move to other locations, households can diversify income sources and spread risks, which in turn can increase their resilience (McLeman and Smit 2006, Black *et al* 2011b, Gemenne and Blocher 2017). Here, migration and *in-situ* adaptation can be two sides of the same coin, for example if households engage in migration and at the same time adapt their agricultural practices. Also the relocation of an entire household can lead to improved protection and adaptation, although researchers have also warned of maladaptation and potential detrimental effects for migrating households and their communities (Warner *et al* 2012, Jacobson *et al* 2019, Vinke *et al* 2020). Given that migration is just one of many coping and adaptation options, it has to be considered against the background of the whole range of options available to households (McLeman and Smit 2006, Pigué 2010).

Despite an increase in public interest in the links between climate change, adaptation, and human migration, empirical evidence on the relationships remains inconclusive (Hunter *et al* 2015, Hoffmann *et al* 2020). Many studies on the topic are localized, with a focus on one community or one country, making it difficult to assess the range of coping and adaptation options used by households to respond to environmental stress and the conditions under which they change their migration behavior. In particular, with regards to the special circumstances faced by rural populations in sub-Saharan drylands, limited comparative evidence exists on climate adaptation and the migration impacts of environmental drivers.

To this end, this review study synthesizes the evidence from 89 case studies from 22 countries on climate change coping and adaptation in SSA. Whereas coping refers to short-term, immediate activities to address, manage, and overcome adverse conditions, adaptation refers to sustained adjustments that are oriented toward longer-term livelihood security (IPCC 2018). As a clear distinction between the two is not always possible based on the reviewed case studies, we speak broadly of adaptation against the

background of the wider literature on climate change and adaptation in developing countries (Mertz *et al* 2009a, Berrang-Ford *et al* 2011, Fankhauser 2017).

Complementing previous reviews on the region (Wiederkehr *et al* 2018, Borderon *et al* 2019), we use a combination of review and quantitative meta-analytical tools to analyze the relationship between environmental change, adaptation, and migration based on a systematic screening of the empirical literature. The focus of our study is placed on rural populations of farmers and (agro-) pastoralists living in drylands south of the Sahara. The meta-data collected as part of our study allows us to effectively compare household behavior across different geographical contexts and populations and to analyze migration against the background of other adaptation activities reported in the case studies.

A novelty from a methodological standpoint is that we combine evidence from both quantitative and more qualitatively oriented case studies, including studies using inference from household and expert interviews or focus group discussions. Most of the considered case studies have a small sample size and provide in-depth insights in the local and contextual settings of the considered communities. This distinguishes our work from previous meta-analyses (Beine and Jeusette 2021, Hoffmann *et al* 2020, Šedová *et al* 2021) that typically consider the environment-migration relationship at more aggregate levels.

Our findings highlight the diversity of adaptation strategies used by households, ranging from agricultural *in-situ* strategies, to the diversification of income sources, the support from social networks, or changes in food provision and consumption. Also, migration as a way of adapting to environmental stress is found to play an important role in some of the communities considered, but not in all of them, depending on the livelihood and ecological context. Considering the use of migration against the background of other strategies, we find that migration is closely linked to and complemented by other adaptation activities. Using cluster analysis, we identify three distinct migration clusters that are characterized by different socioeconomic profiles and levels of vulnerability, suggesting that migration in response to environmental change can take various forms along a continuum from coerced to more voluntary forms of migration.

The remainder of the paper is structured as follows. Section 2 provides further information on the context in SSA drylands and discusses some of the pertinent challenges faced by local populations. Section 3 introduces the research design and literature basis used and presents our screening and study selection process. Section 4 presents the main findings, which are discussed in section 5. Section 6 concludes.

2. The context: drylands in sub-Saharan Africa

Drylands are commonly defined on the basis of the aridity index (AI), which is the ratio of annual potential evaporation to precipitation (Safriel *et al* 2005). Drylands are areas with an AI of 0.65 or less. They can be further divided into hyper arid ($AI < 0.05$), arid ($0.05 \leq AI < 0.20$), semi-arid ($0.20 \leq AI < 0.50$), and dry sub-humid ($0.50 \leq AI < 0.65$) zones. Higher aridity within drylands is typically associated with lower population density, with hyper arid zones being only sparsely populated. Drylands are important for food production in SSA, accounting for 66% of cereal production and 82% of livestock holdings in the region (Cervigni and Morris 2016). Livelihood strategies are centered around agriculture, with populations in drier areas being mainly involved in pastoralism and those in less arid areas relying on rain-fed cultivation.

Drylands are characterized by challenging agroclimatic conditions, including high precipitation variability and chronic water scarcity (figure 1). They are exposed to a number of environmental hazards and changes and are frequently affected by weather extremes and droughts, which can result in widespread crop and livestock loss (Huho *et al* 2011, Middleton and Sternberg 2013). Although dryland inhabitants are adapted to their environments, the frequency and severity of climatic shocks is increasing under climate change (Diffenbaugh *et al* 2017) putting additional pressure on local livelihoods (Thornton *et al* 2011).

For pastoralists and agro-pastoralists, the shrinkage of grazing areas is a major problem and these mobile populations respond by travelling further distances. Farmers are affected by delays in rainy season onset, mid-season heatwaves and heavy rains resulting in crop loss and low yields (Connolly-Boutin and Smit 2016). Frequent exposure to environmental hazards has been linked with the depletion of household assets, particularly among the poor who are not able to smooth consumption (Carter *et al* 2005, Ansah *et al* 2020).

Moreover, population growth and environmental degradation are fueling disputes in the sub-Saharan drylands. An increase in conflict between farmers and semi-nomadic herders has been documented due to the increased competition for resources between the two groups (UNEP 2011, Brottem 2016). Certain population subgroups are also socially and politically marginalized, which further exacerbates their vulnerability to climate change and conflicts (Fjelde and von Uexkull 2012).

Besides climate change, human activity is also speeding up land degradation in the area, which is expected to have far-reaching consequences for food security, economic activity, and population health in the region (United Nations Economic and Social Council 2007). Land degradation is often the result

of unsustainable use of land by smallholder farmers who lack the capacity to invest in more sustainable practices (Shiferaw *et al* 2014). Consequently, land degradation increases vulnerability to environmental stress even further, which leaves subsistence farmers in a vicious cycle.

Given that populations in sub-Saharan drylands are directly dependent on the natural environment for their livelihoods and are frequently affected by severe weather events, poverty is pervasive in the region (Middleton *et al* 2011). In fact, drought-sensitive countries in SSA have seen an increase in the prevalence of undernutrition from 17.7% in 2010 to 21.8% in 2018 (FAO, IFAD, UNICEF 2019). In the past years, extreme events triggered several million internal displacements, most notably in Eastern and Western Africa. Across all regions, an increase in internal and international migration was also observable (supplementary figure S1).

3. Review methods and study selection

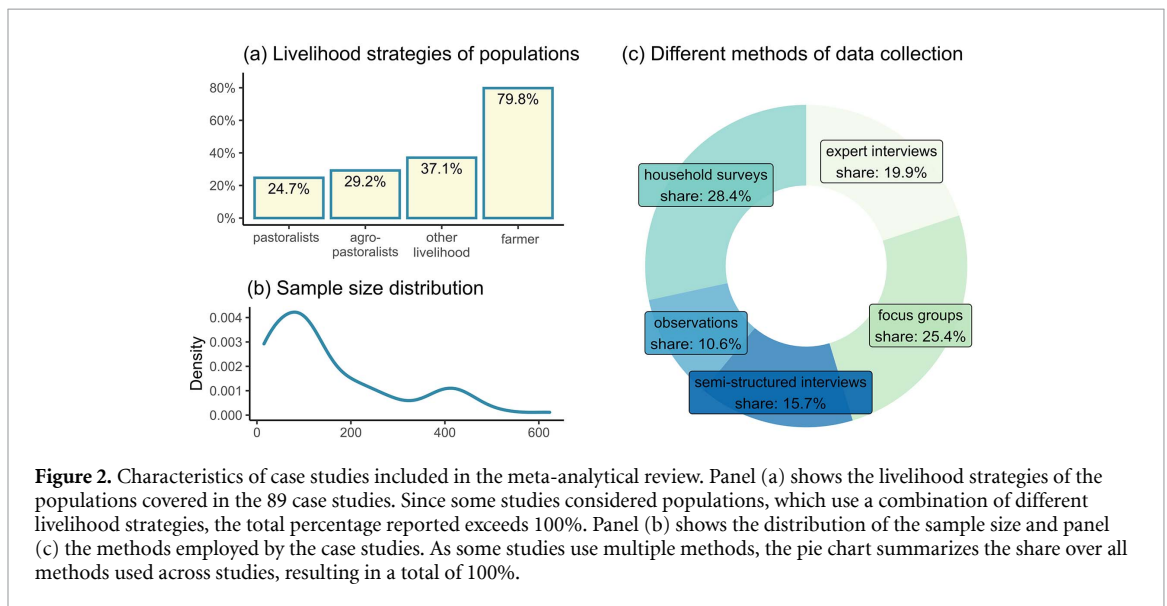
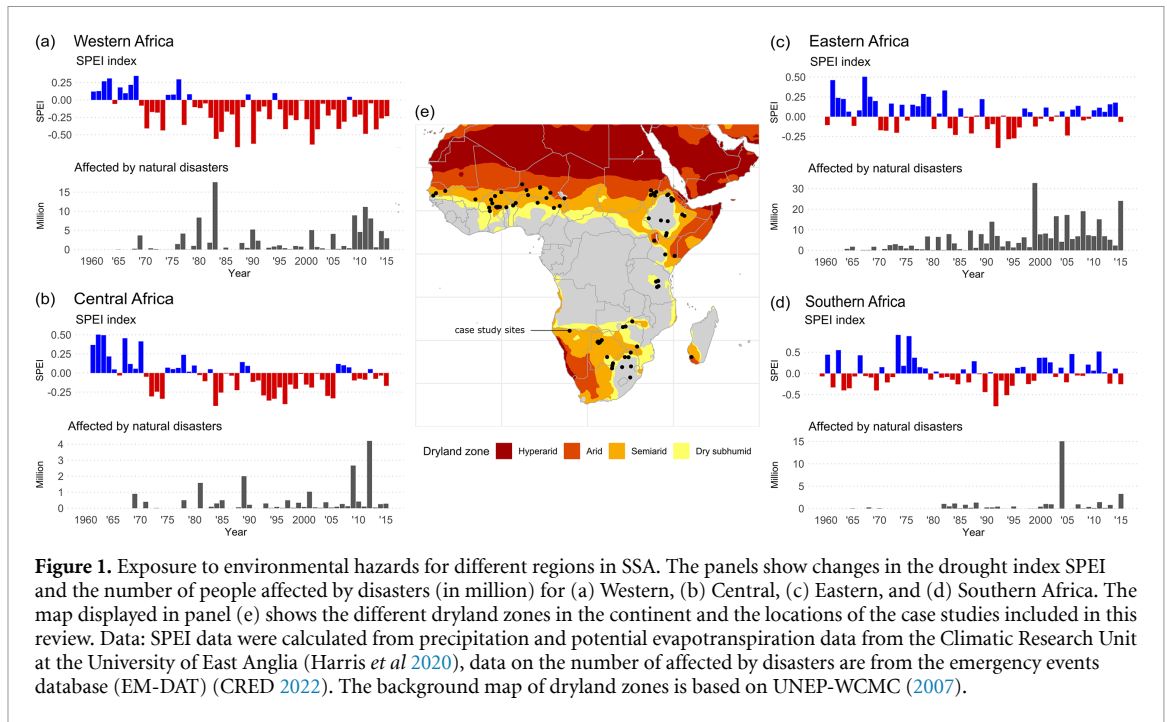
3.1. Literature search and screening

The literature search for this study was conducted in two stages—a first stage in June 2017 and a second stage in March 2020 when newer studies were added to the initial selection (Wiederkehr *et al* 2018). We followed a stepwise procedure to identify relevant studies for our review. In a first step, a systematic search of studies was carried out on the scientific search platform ‘Web of Science’, which provides comprehensive citation data for various academic fields. We used relevant keywords, including the names of all countries in SSA, terms related to environmental change and associated hazards, and the terms ‘adapt’ and ‘cope’. More information on the specific search terms can be found in supplementary material B.

The entire search process yielded a preliminary selection of 3625 papers, which were further examined and filtered (see supplementary figure S2 for a PRISMA diagram). The filtering involved two steps. First, the relevance of papers was assessed based on their titles, keywords, and abstracts. In a second step, the full texts were thoroughly assessed for eligibility based on predefined inclusion criteria. We only considered peer-reviewed articles published in English.

The following inclusion criteria were used to determine the eligibility of studies. A paper was considered eligible, if it (i) comprised primary data from a local case study, (ii) focused on populations in predominantly rural and (semi-)arid areas characterized by subsistence livelihoods or small-scale agricultural activities, (iii) reported an environmental change process⁷, (iv) presented data at the household

⁷ In our screening, the text-based information was interpreted literally, i.e. dynamic terms like ‘increase’, ‘decrease’, or ‘degradation’ were understood as reflecting change processes.



level, (v) provided information on multiple coping and adaptation strategies (excluding preferred or planned actions), and (vi) provided information on the percentage of households in a study population adopting specific strategies.

The search and selection procedure resulted in a total sample of 89 individual case studies covering more than 21 thousand households in 22 countries (see supplementary table S1 for a full list of studies). Information on the case studies were retrieved from 53 distinct articles, which were published between 2004 and 2019. The studies were conducted in different regions in SSA and used a variety of research designs and methods (figure 2(c)). Household surveys, focus groups, and key informant or expert interviews were the most common data

collection methods, often complemented by semi-structured interviews and field or participant observations. Sample sizes ranged from 15 to 623 participants, with most studies based on fewer than 200 participants (figure 2(b)).

The dryland locations covered by our sample of case studies are exposed to a range of environmental changes and hazards. Most commonly, studies reported changes⁸ in the amount of rainfall (71.9% of studies) as well as more unpredictable and erratic rainfall (48.3%), increasing temperature levels (67.4%), and drought (41.5%) as major

⁸ Depending on the study, this information is based on perceptions by the local study population, measurements by the respective researchers, or secondary data.

sources of environmental stress. Also, risks related to the degradation of land (58.4%) and water bodies (31.5%) were frequently mentioned. These include issues related to soil erosion (10 study cases), lake drying (4 cases), and the desiccation of floodplains (1 case). Other mentions relate to risks of flooding (18.0%) and stress related to wind (10.1%), especially increasing wind speeds (7 study cases) or the occurrence of dust storms (4 cases).

3.2. Data and measurement

From each article, we extracted information about the study location(s), period of data collection, other study characteristics and results, which became the basis of our meta-data. We use this information to compare result patterns across studies and explore whether these were influenced by contextual factors at the household and community level. We are primarily interested in the adaptation strategies used by households, which we classify in 14 broad categories. In each category, we calculated the percentage of households among the study population who reported the adoption of a specific type of strategy. Table S1 in the supplementary materials gives examples of adaptation measures reported in each of the 14 categories. Typically, the households reported the use of several measures belonging to one category at a time. This means that in certain categories several percentage values were recorded, the sum of which may exceed the value of 100%.

Based on the information retrieved from the studies, we constructed two main outcome variables for each of the 14 adaptation categories: (i) A dummy variable taking the value of one if any measures belonging to a specific category were reported in the study population and zero otherwise, and (ii) a continuous variable which corresponds to the share of households using the most common measure in a category. The latter measure provides a conservative lower bound estimate of the share of households using measures in each of the 14 adaptation categories. For our main analyses, we rely on the continuous outcome. Results using the dummy variable are reported in the supplementary materials (supplementary figure S3). Importantly, both the dummy and the continuous outcome variables are comparable across categories and across studies, which allows us to investigate what the most common forms of adaptation are, and in which context they are most likely to be used.

In addition to the measures described above, we retrieved information from each article about the mode of data collection, characteristics of the interviewed households, indications of environmental change processes, and other environmental and non-environmental factors relevant for the local context.

One key piece of information which was retrieved from the studies is the predominant livelihood strategy among interviewed households. We used this information to categorize study populations in three types: sedentary farmers, (agro-)pastoralists, and mixed populations who use a combination of both farming and (agro-)pastoralism (figure 2(a)). Among the different livelihood strategies, farming was the most common across study populations, with nearly 80% of households on average involved in some form of farming activities.

We aimed to collect the precise global positioning system (GPS) coordinates (latitude and longitude) of the study populations. Some studies did not report GPS coordinates, but we managed to determine the approximate location of study sites based on available information, for example the name of the district in which the study was carried out. Once the GPS coordinates of each study location were determined, we were able to join the meta-data retrieved from the articles with external data sources. In particular, we added information about the overall socioeconomic conditions in the region, which may influence the adaptation options available to households.

We retrieved information about the overall socioeconomic conditions from Demographic and Health Surveys (DHS)—large and nationally representative household surveys conducted in over 90 low- and middle-income countries, including most countries in SSA. The DHS data are representative at the subnational level, which is usually based on the census enumeration areas in the respective country (for example region or district). Various contextual information were obtained from DHS and aggregated at the lowest representative enumeration area for the respective DHS survey. In particular, we calculated: (i) the percentage of households employed in agriculture, including both farmers and (agro-)pastoralists, as a proxy for agricultural dependence, (ii) the percentage of households with access to electricity and with a finished (non-natural) floor as wealth proxies, and (iii) the percentage of households with secondary education and higher as a proxy for adaptive capacity related to education. To assign accurate background information to the case studies, we used DHS data from the same period when the data for the original studies were collected. If studies were missing information about the exact data collection period, we used the publication year as reference point.

3.3. Analytical tools: identifying adaptation patterns across studies

We employed a range of analytical tools to identify adaptation patterns across the studies included in the analysis. The texts were comprehensively screened and relevant data concerning study context, methods,

and findings were extracted into a spreadsheet. The distribution of adaptation patterns across studies was explored and described using quantitative methods and descriptive graphs for illustration. In addition, we reviewed and coded the texts to contextualize the findings from the studies and to provide an in-depth perspective and examples on how the study populations responded to environmental changes. Here, we primarily identified common protective and adaptive activities employed by households as well as challenges reported.

In this study, we are particularly interested in migration and how it is used in combination with other strategies depending on the ecological and socioeconomic context. The primary goal is not to consider migration in isolation, but to understand its links to adaptation in a community more broadly. To this end, we consider differences in response patterns conditional on characteristics of the local populations represented by the studies. Matching case study locations with external socioeconomic data derived from DHS allows us to complement the information provided in the studies with wider contextual measures and effectively compare the different study contexts with each other.

Cluster analysis is used to identify adaptation clusters within the case study sample, i.e. populations using similar strategies, and to determine the socioeconomic conditions associated with certain combinations of adaptation activities. For the clustering, we use a centroid-based k-means clustering approach, which partitions the observed study cases x into a set C of k different clusters so as to minimize the within-cluster sum of squares (WCSS), i.e. the difference of each observation from the mean μ_i within each cluster C_i .

$$\arg \min_s \sum_{i=1}^k \sum_{x \in C_i} \|x - \mu_i\|^2 \quad (1)$$

The number of clusters k is defined prior to the clustering and we employ various tests to identify the optimal number in our application (see supplementary materials E). x represents a vector of the percentage of households in a study sample using the different adaptation strategies. The cluster analysis is performed in R using the *cluster* package (Maechler *et al* 2021) and the Hartigan and Wong algorithm (1979). The algorithm assigns data points to a randomly created initial set of clusters based on their difference to the cluster centroids and calculates changes in the WCSS (1) if the data point were to be included in another cluster. If the resulting WCSS is smaller than in the original assignment, the data point is assigned to this new cluster. This iteration continues until the assignment is stable, i.e. no more improvements in the WCSS criterion can be reached by changing cases between clusters. In this situation, any

change would make the clusters more internally variable or more externally similar and thus increase the WCSS.

4. Results

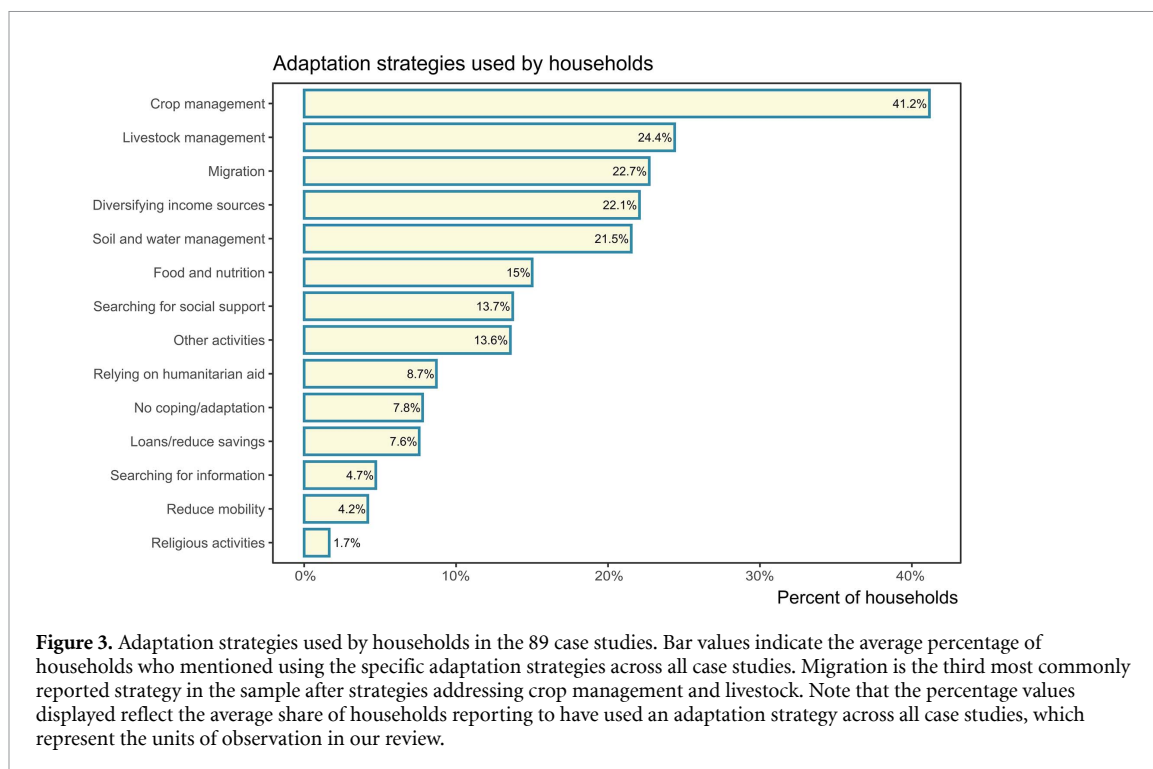
4.1. Households rely on diverse adaptation strategies

Households use a diverse range of strategies to cope with and adapt to the environmental changes observed (figure 3). Agricultural strategies, including measures related to crop cultivation (41.2%), live-stock keeping (24.4%), and soil and water management (21.5%), are clearly the most common, likely reflecting the predominance of sedentary farmers in our sample of studies. This also indicates a tendency of households to adapt *in-situ* and continue with agriculture rather than completely abandon cropping or herding. The reliance on *in-situ* activities could be due to socio-cultural reasons that induce people to stay in their current place of residence, such as place attachment (Vinke *et al* 2020), or it could be due to barriers and constraints in mobility (Cattaneo and Peri 2016).

The agricultural strategies cover a broad range of activities further highlighting the diversity of adaptation measures used by rural households. As part of the most commonly reported category, crop management, households report changes in their use of fertilizer and compost (e.g. Barbier *et al* 2009, in Burkina Faso; Mertz *et al* 2009b, in Senegal), the use of more resistant crop varieties (e.g. Tambo and Abdoulaye 2013, in Nigeria; Okpara *et al* 2016, in Chad), the diversification of crops (e.g. Gebrehiwot and Van Der Veen 2013, in Ethiopia; Antwi-Agyei *et al* 2014, in Ghana), changes in crop rotation (e.g. Padonou *et al* 2014, in Benin; Yila and Resurreccion 2014, in Nigeria), and modifications in the farmland (e.g. Snorek *et al* 2014, in Niger; Tesfaye and Seifu 2016, in Ethiopia).

A broad variety of other (non-agricultural) strategies are also used by the households. These include short-term strategies, such as the search for aid (8.7%) or support within the social network (13.7%), or financial measures, such as taking loans or dissolving savings (7.6%). Changes in food consumption and provision are also often reported (15%). In many study contexts, these changes reflect adaptation challenges and heightened levels of vulnerability of affected populations. Some studies report changes in diets, such as an increase in the consumption of wild plants or fruits (Osahr *et al* 2010, in South Africa; Bola *et al* 2014, in Zimbabwe) or low quality famine foods (McKune and Silva 2013, in Nigeria).

Others find that households reduce their food consumption to cope with environmental stress, e.g. by eating less (Silvestri *et al* 2012, in Kenya), eating



fewer meals per day or skipping meals (Hänke *et al* 2017 in Madagascar; Mubaya and Mafongoya 2017, in Zimbabwe; Pauline *et al* 2017, in Tanzania), or refraining from eating for a whole day (McKune and Silva 2013, in Nigeria). In some communities, households were forced to sell their assets and livestock to buy food (Chianu *et al* 2004, in Nigeria; Yaffa 2013, in Gambia) or relied on external support and food aid (Silvestri *et al* 2012, in Kenya; Ariti *et al* 2015, in Ethiopia).

Of all households considered in the studies, on average 7.8% reported to not have used any adaptation strategy. While this might reflect lower levels of exposure to hazards, it could also indicate the presence of adaption barriers. For the case of Ethiopia, Gebrehiwot and Van Der Veen (2013) show that lack of information on adaptation measures and insufficient access to finance are two important factors inhibiting adaptation to climate change (see also Tambo and Abdoulaye 2013, for Ghana, Gbetibouou *et al* 2010, for South Africa).

The availability of information and experiences influence whether and how people perceive environmental risks and how they respond to them. At the same time, adaptation requires financial and other resources, which might not be accessible to all households, e.g. because of insufficient access to agricultural inputs, technologies or credit markets. To better understand household responses to environmental changes, there is a need to consider the wider context in which they take decisions, including their perception of environmental hazards and potential resource constraints (Koubi *et al* 2016).

4.2. Migration is common and used in a variety of ways

Besides agricultural strategies, migration is among the most common strategies reported by the interviewed households. Across all case studies, nearly one out of four households stated to have used some sort of migration as a means to deal with environmental change. As such, it constitutes an integral part of the adaptation options used by rural households in SSA. The *in-situ* diversification of income sources, which often goes hand in hand with migration (Wuepper *et al* 2018), was reported by 22.1% of households. In our classification, we treated *in-situ* diversification and migration as two separate categories to distinguish them in the analysis. Migration can serve the purpose to diversify income sources *ex situ*, which was also mentioned as an important motive for migration by several of the reviewed studies (Osbaahr *et al* 2010, Dumenu and Obeng 2016).

Of the 17 case studies with very high levels of migration (mentioned by >50% of all households), 12 (70.6%) were conducted in the Sahel region. Typically, the migration patterns reported by households in these studies were internal within the same country or region. For example, vulnerable communities in Northern Ghana had a long history of migration to Southern Ghana, especially by young men, to engage in farm or off-farm wage labor (Antwi-Agyei *et al* 2014, Ngwese *et al* 2018). A similar pattern was observed in a study from Northern Burkina Faso, where household members primarily migrated to the South of the country where land was still available or to neighboring Ivory Coast to work on cocoa

plantations (Barbier *et al* 2009). In Niger, households reported the neighboring countries of Libya and Nigeria as primary migration destinations (McKune and Silva 2013).

Seasonal migration for a restricted time was very common among the study populations. In Chad, Botswana, and Burkina Faso, for example, households were found to travel to resource-abundant areas for collective livestock grazing or fishing (Motsholapheko *et al* 2012, Okpara *et al* 2016), highlighting the importance of mobility for communities depending on herding and transhumance (see also section 4.3). In Kenya, Turkana herders frequently moved across borders, especially to Uganda, South Sudan, or Ethiopia, to access resources and markets (Opiyo *et al* 2015). Similar patterns of livestock-related seasonal mobility were reported for Ethiopia (Berhanu and Beyene 2015) and Zimbabwe (Mubaya and Mafongoya 2017).

While temporal forms of mobility were found to be common in the considered sample of studies, also more permanent forms of outmigration were used. In Burkina Faso, for example, the majority of study participants considered permanent migration to other parts of Burkina Faso or to Ghana/Ivory coast a viable strategy if climate change impacts worsen (Zampaligré *et al* 2014). New international destinations are also becoming more attractive for migration from the region. For example, international labor migration from Ethiopia and other Eastern African countries to the Arab states of the Persian Gulf is a growing trend (Mersha and Van Laerhoven 2016).

If migration is used, it is typically only individual household members who migrate and not the entire household (Smucker and Wisner 2008, Barbier *et al* 2009, Dumenu and Obeng 2016). In the sub-Saharan context, migrants are usually young men who migrate for economic reasons to find work or to engage in seasonal jobs. In search for better opportunities, many migrate internally toward urban centers (Clement *et al* 2021), which is also reflected in several of the case studies (e.g. Yaffa 2013, in Gambia; Dumenu and Obeng 2016, Kumasi *et al* 2019, in Ghana). This contributes to the rapid urban growth observed in SSA, which is the world region with some of the fastest growing cities worldwide (Hoffmann and Muttarak 2021).

Remittances play an important role for mobility in the area and migrants usually maintain close ties to their home regions. Even if migration in the considered studies is not explicitly framed as 'economic', it is often mentioned in association with job search or remittances (Snorek *et al* 2014, Yila and Resurreccion 2014, Ngwese *et al* 2018). This also highlights the multicausal nature of mobility, which is typically influenced not only by one, but a range of different economic, sociopolitical, demographic, and environmental factors (Black *et al* 2011a).

4.3. Livelihoods and ecological conditions shape migration patterns

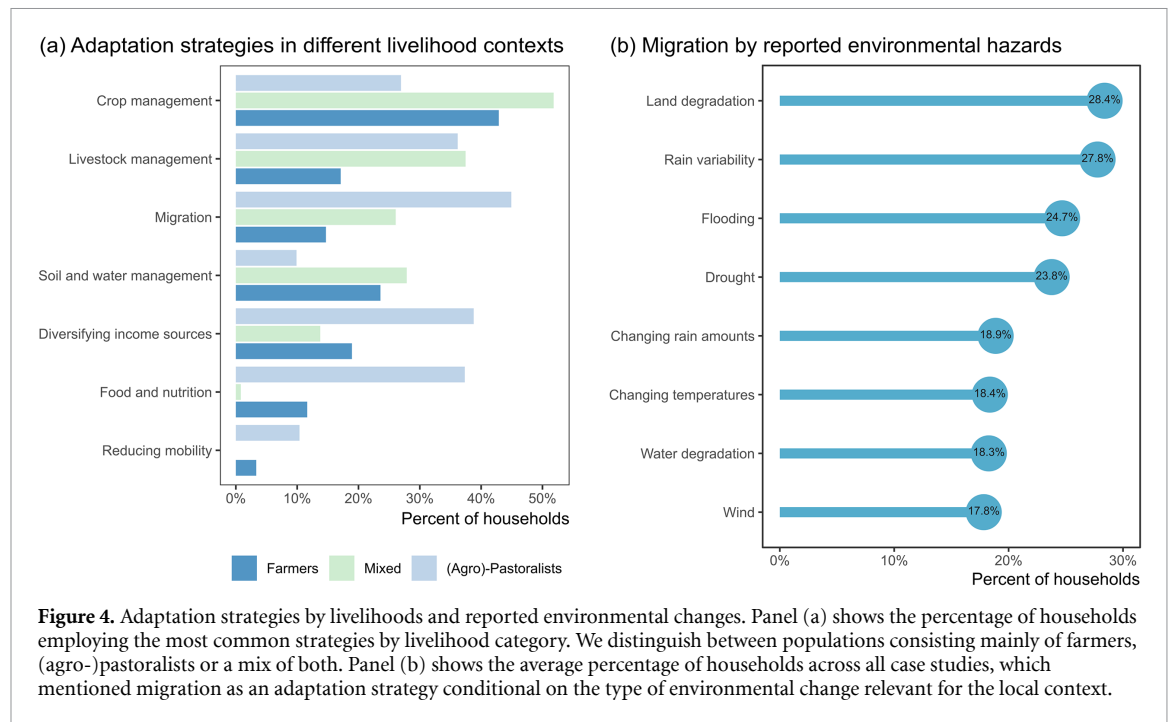
The relationship between environmental factors and migration is not uniform but depends on the local livelihood and ecological conditions (figure 4). While *in-situ* adaptation strategies, such as changes in cultivation practices or soil and water management, are most often reported in studies focusing on farmer populations, migration is clearly most common among (agro-)pastoralists. In those highly mobile communities, the role of environmental change processes has to be understood against the background of existing forms of mobility (e.g. transhumance), which are influenced by a range of factors (Boas *et al* 2019).

These populations are also more likely to report diversification (38.8%) and changes in food consumption (37.3%) as ways to cope and adapt when confronted with environmental changes and hazards (figure 4(a)). In many instances, migration in search for better economic opportunities were also reported. In Ngamiland, Botswana, for instance, high percentages of respondents stated to migrate to towns for wage labor in the context of pastoral rangeland degradation (Basupi *et al* 2019). Similarly, a study from Kenya mentions out-migration of agro-pastoralists in search of paid work (Smucker and Wisner 2008). There might be several reasons for the higher prevalence of migration among (agro-)pastoralist households, which we discuss in greater detail in section 5.

In rare cases, households reported the reduction of mobility (4.2%) as a way to deal with an environmental hardship (McKune and Silva 2013). This strategy was again most commonly reported by pastoralist populations, who might have had to settle temporarily if they were unable to sustain their livelihood with a nomadic lifestyle. This is also exemplified by Basupi and colleagues (Basupi *et al* 2019), who report an increasing dependency of pastoralists on social welfare programs due to the high uncertainty of pastoral income (resulting i.a. from livestock diseases and restricted access to productive rangelands) and lacking alternative income sources.

Whether or not migration is used by communities in the drylands is found to also depend on the reported environmental changes (figure 4(b)). Most commonly, households listed migration as a strategy in the context of land degradation (28.4%), rainfall variability (27.8%), flooding (24.7%) and drought (23.8%). All of these stressors are directly linked to agricultural production and can be particularly destructive in dryland areas characterized by overall low precipitation and high temperatures (Falco *et al* 2019).

Typically, communities in the studies were exposed not only to one, but to multiple changes and hazards in their environments. Environmental impacts are not independent of each other, but are



closely correlated and can co-occur (Hoffmann *et al* 2021). In additional analyses, we find that certain types of environmental stressors were often jointly reported by the case studies (supplementary table S4 and figure S4). For example, changes in rainfall amounts were often mentioned together with challenges arising from changing temperature levels, and drought hazards with changes in rainfall variability, land degradation, and flooding. Especially the co-occurrence of different stressors requires a combination of strategies to adapt to the changes (adaptation mix). With increasing levels of environmental stress, a threshold may be reached beyond which *in-situ* adaptation may no longer be sustainable for local populations (Warner *et al* 2012, Dow *et al* 2013, Xu *et al* 2020).

4.4. Households use a combination of adaptation strategies

The individual adaptation strategies are rarely used in isolation. Instead, households use a combination of different strategies to adapt to environmental changes and hazards (figure 5). Interviewed communities in Botswana, Benin, South Africa, or Kenya reported a mix of eight or nine different strategies to deal with experienced environmental changes (Osbahr *et al* 2010, Opiyo *et al* 2015, Oyerinde *et al* 2015, Basupi *et al* 2019).

In one community in Burkina Faso, for example, a large share of households used combinations of changes in cultivation practices, livestock, and soil and water management (Mertz *et al* 2012), whereas another community in Ghana more heavily relied on income diversification, social contacts, adjustments

in food consumption and external aid in combination with migration (Antwi-Agyei *et al* 2014). Although the papers reviewed here indicate how many strategies were reported in total, they do not provide specific information on how many households actually applied several or all of them simultaneously. This still constitutes a missing piece of information to better understand the dynamics between different strategies, including migration (see also Wiederkehr *et al* 2018).

To understand households' responses to environmental stress, strategies have to be considered in a wider context of adaptation behaviors as these are closely linked to each other and correlated. In the literature, there is evidence that households tend to adopt several strategies simultaneously (Silvestri *et al* 2012, Mogotsi *et al* 2013, Hooli 2016, Tesfaye and Seifu 2016, Hermans and Garbe 2019). These strategies can either complement or substitute each other.

Figure 5(a) shows the correlation of the share of households using different adaptation strategies across the sample of studies. Some of the strategies are highly positively correlated and seem to complement each other. For example, changes in crop management are often named in combination with soil and water conservation measures (but not livestock), and the search for social support is often named together with the diversification of income sources, changes in food consumption and provision, and external aid.

In our explorative analysis, strategies are found to be in most cases either uncorrelated or positively correlated suggesting positive complementarities.

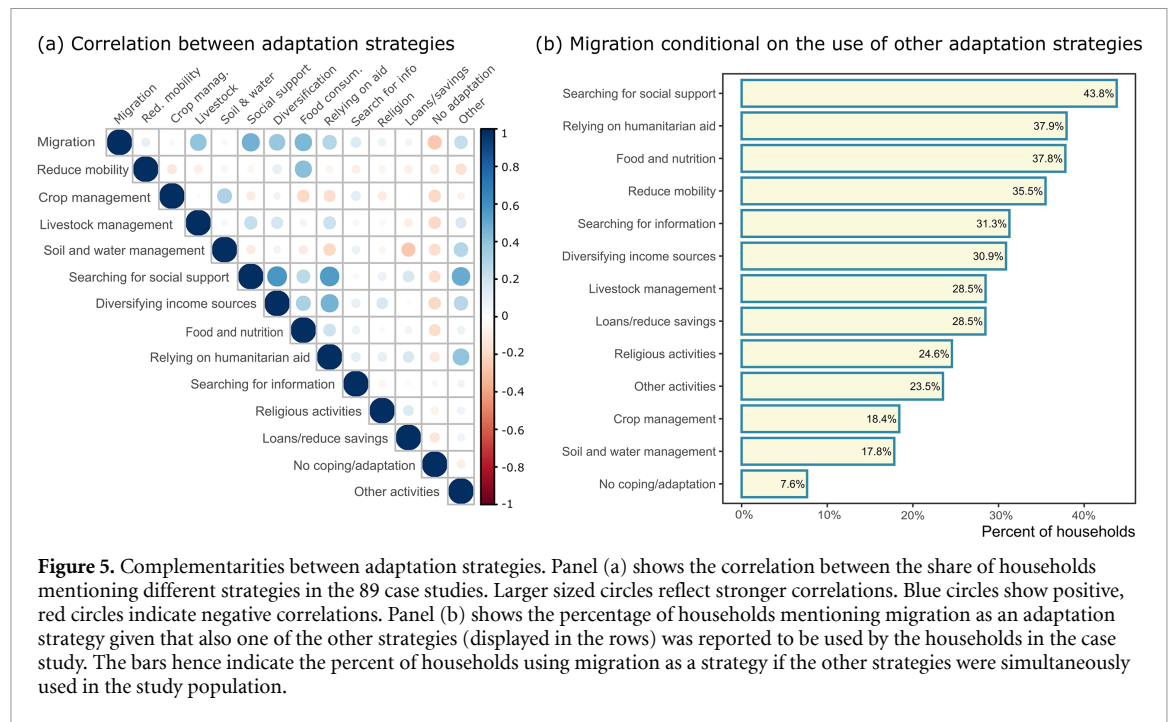


Figure 5. Complementarities between adaptation strategies. Panel (a) shows the correlation between the share of households mentioning different strategies in the 89 case studies. Larger sized circles reflect stronger correlations. Blue circles show positive, red circles indicate negative correlations. Panel (b) shows the percentage of households mentioning migration as an adaptation strategy given that also one of the other strategies (displayed in the rows) was reported to be used by the households in the case study. The bars hence indicate the percent of households using migration as a strategy if the other strategies were simultaneously used in the study population.

Likewise, based on data from surveyed households in Ghana, Tambo (2016) states that the majority of analyzed strategies act as complements, not substitutes. For Kenya, Tongruksawattana and Wainaina (2019) identified farm adjustments as a substitution strategy for selling assets and borrowing for drought adaptation, whereas a complementary reduction in consumption was observed for households who were forced to borrow money. Eriksen et al (2005) conclude that during periods of environmental distress households usually adopt one principal adaptation strategy that is complemented by other secondary measures.

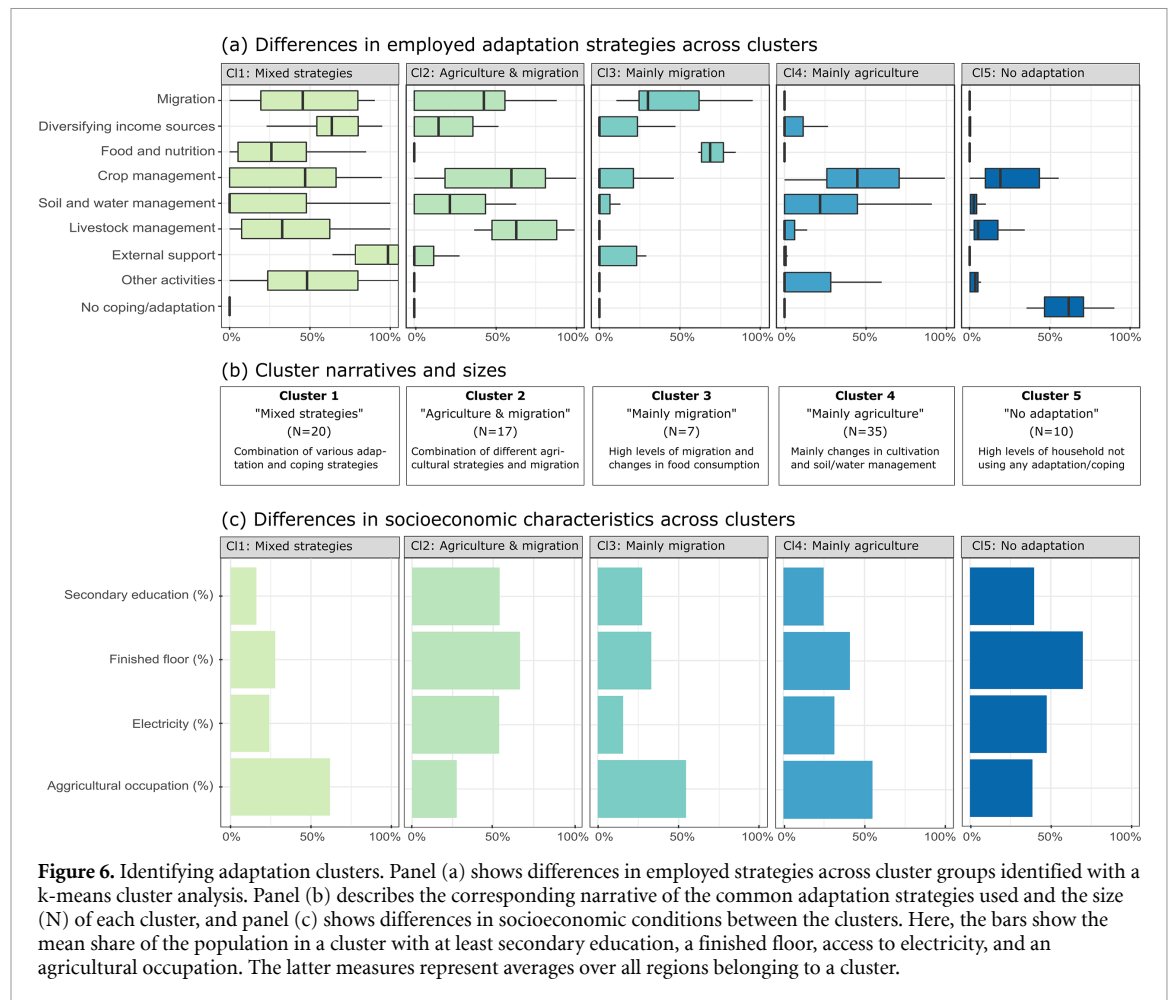
Migration, like the other strategies, is only one of many potential responses to environmental stress and has to be analyzed against the background of other strategies and activities of the households (McLeman and Smit 2006, Perch-Nielsen et al 2008, Piguet 2010). Figure 5(b) shows the average percentage of households mentioning migration conditional on whether other strategies were used simultaneously by the households. Migration is commonly reported with other strategies, such as the search for social support, relying on humanitarian aid, changes in food consumption and provision, search for information, the diversification of income sources, and livestock management. On the other hand, we do not find a strong correlation between migration and the use of other more sedentary forms of agricultural adaptation, such as changes in cultivation and soil and water management. This also mirrors our findings on livelihood-specific differences in adaptation choices addressed in section 4.3, with migration being more common among (agro-)pastoralist households.

4.5. Identifying adaptation clusters

Focusing on the nine most common adaptation strategies, we conducted a cluster analysis to identify clusters of study populations using similar strategies when confronted with environmental change and hazards (figure 6). For this, we follow a stepwise procedure to determine the optimal number of clusters and explore the resulting cluster assignment (supplementary materials E). Our cluster analysis reveals five distinct adaptation clusters from a total of 89 cases. The analysis allows us to explore cases with a similar adaptation profile and to reveal the interconnectedness of different strategies employed in the surveyed communities. It also illustrates patterns and differences in adaptation across the studied settings.

Figure 6(a) shows the distribution of adaptation strategies across the clusters with higher values representing a greater share of households in a cluster using a strategy. Figure 6(b) shows the corresponding narrative and size of each cluster and figure 6(c) combines information about the location of the clusters with background information about the local socioeconomic conditions to explore under which conditions certain clusters are most likely to occur. Here, we consider the average percentage of the population in a cluster with at least secondary education, a finished floor, access to electricity, and an agricultural occupation. The latter measure accounts for both the share of farmers and (agro-) pastoralists in the population, which are not distinguished in the DHS.

Three of the considered clusters (1–3) are migration clusters with an increased share (median share > 25%) of households using migration as an

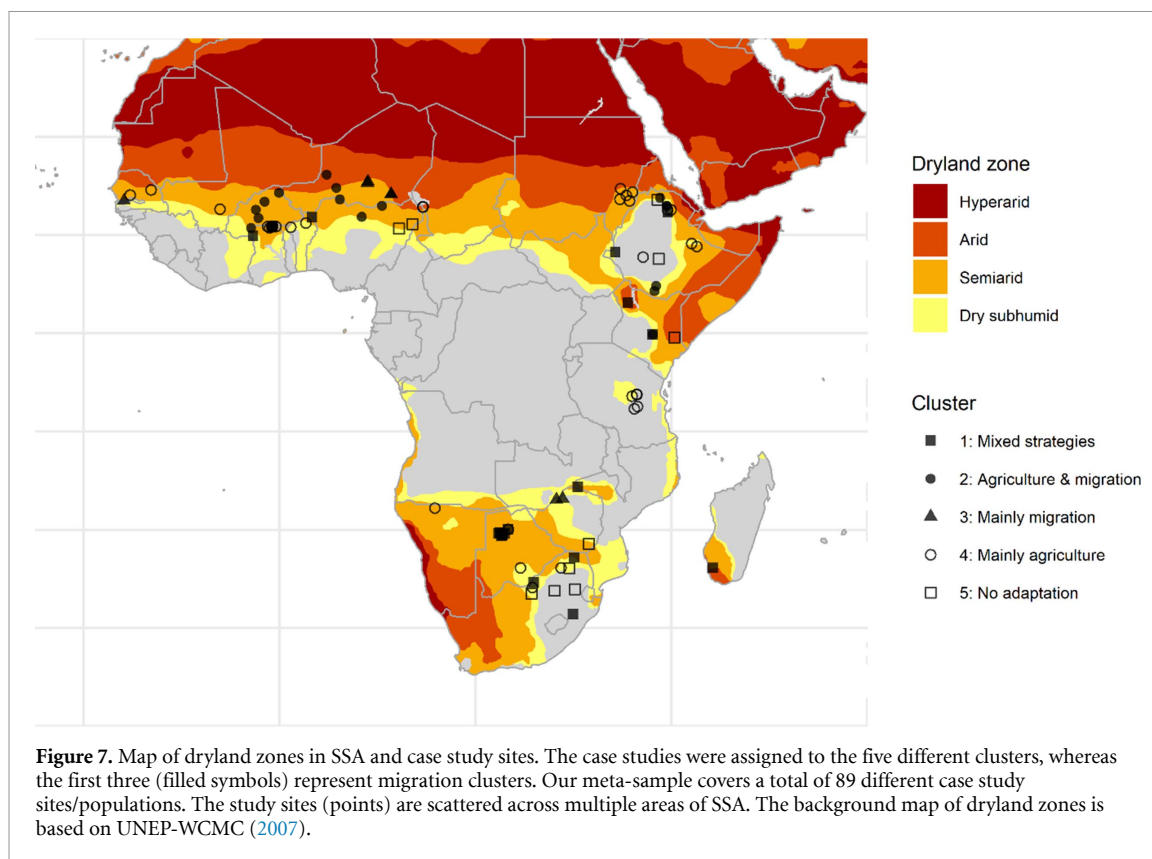


adaptation strategy. The geographic location of the migration clusters is shown in figure 7. As can be seen from this figure, clusters with high levels of migration (filled symbols) can be primarily found in the western and central Sahel region as well as in selected locations in East and Southern Africa. While all three migration clusters can be characterized by increased levels of human mobility, they are distinct in their use of complementary strategies. A form of adaptation that is closely related to migration are activities related to the diversification of income sources. For all migration clusters, increased levels for this strategy can be observed, indicating a complementary relationship between both strategies.

The important role of context and socioeconomic influences is apparent in all results. Whereas migration is found in both areas with a higher and lower level of development, differences are visible in the combination of strategies used. In particular, high levels of poverty, limited access to education and information, lacking social protection, inequality and uneven development processes, weak institutions, and limited access to financial, labor, and agricultural markets have been identified in the case studies as major inhibitors to achieving climate resilience at large (Ng'ang'a *et al* 2016, Pauline *et al* 2017).

The first 'Mixed Strategies' cluster ($n = 20$ case study populations) uses migration in combination with a wide variety of other strategies, ranging from attempts to diversify income sources, to search for external support via social networks or aid organizations, or to engage in other adaptation activities. Also changes in food consumption, e.g. changes in diets or reductions of food intake, are reported by a considerable share of households in this cluster (median $> 25\%$), which we consider as a sign of populations facing challenges in their adaptation, potentially contributing to increased vulnerability. Indeed, considering the socioeconomic profile of this cluster, it is most commonly found in more deprived areas where only a very low percentage of the population has access to basic infrastructures, such as education and electricity, and where livelihoods strongly depend on agricultural occupations.

The second 'Agriculture & Migration' cluster ($n = 17$) uses migration in combination with different agricultural strategies, both relating to changes in cultivation, soil and water management, and livestock keeping. Also attempts to diversify income sources play a role, but to a lesser extent. Unlike the first cluster, this cluster is characterized by a relatively higher socioeconomic status with on average more



than 50% of populations in the regions having completed secondary education, having access to electricity, and having a finished floor. Also, only a comparably low share of the communities in this cluster directly depend on agriculture, suggesting greater opportunities to diversify income sources to adapt to environmental change. In this context, migration is often described as a complementary strategy used to support the household income, including mobility in search of wage labor (Smucker and Wisner 2008 in Kenya), seasonal mobility (Rasmussen 2018 in Burkina Faso), and herding-related mobility (Berhanu and Beyene 2015, Ng'ang'a *et al* 2016, in Ethiopia).

The third 'Mainly Migration' ($n = 7$) cluster represents populations where a large share of households report using primarily migration as a form of adaptation. While in some communities also agricultural strategies are employed, the majority of communities in this cluster do not use any of these strategies (median = 0). The only notable exception reported by the households are strategies related to food and nutrition. On average, more than 60% of households indicated that they changed their diets or made additional efforts to obtain food to react to environmental changes, which might reflect limited *in-situ* adaptive capacities and increased levels of stress. Like the first cluster, this cluster is characterized by a weaker socioeconomic profile, suggesting

a close relationship between human development, vulnerability, and adaptation. Unlike the second cluster, agricultural dependence is high and migration and changing food consumption seem to serve as strategies of last resort here. While this observed pattern can be found in only few of the considered study populations, it hints toward a reduced ability of certain populations to withstand environmental pressures and a lack of viable adaptation options, making migration the only suitable strategy to deal with environmental hardships. While migration is described as an adaptation mechanism by study populations, it can also come with significant long-term repercussions for migrants and their families, for example negative health impacts (Yaffa 2013, in Gambia) or increased divorce rates (McKune and Silva 2013, in Niger).

The fourth 'Mainly Agriculture' ($n = 35$) cluster is the biggest of all clusters. Households in this group primarily rely on *in-situ* agricultural adaptation strategies, such as changes in cultivation and soil and water management. Migration, on the other hand, is not found to play a major role. The focus on agriculture in adaptation is also reflected in the background variables, which reveal that regions belonging to this cluster are characterized by a high agricultural dependence with on average more than 50% of the populations having an agricultural occupation. In general, the cluster is characterized by a

weaker socioeconomic profile with less than 30% of the populations having completed secondary education and having access to electricity. Most commonly, households in this cluster use a combination of crop and soil and water management techniques to adapt to environmental changes. For example, households in a study in Burkina Faso (Mertz *et al* 2012) were found to use a combination of manure application and fertilization methods together with soil and water conservation, reforestation, improved irrigation, and vegetation protection (e.g. stone bunds, fallow periods) methods.

The final 'No Adaptation' cluster ($n = 10$) is a cluster where only very few households make use of the considered adaptation strategies. Communities belonging to this cluster are characterized by a relatively high level of education (>50% with secondary), comparably good access to electricity (>40%), and well-developed housing structures (>70% with finished floor). While all case studies included in this cluster were primarily focused on crop and livestock farmers, the considered communities were located in regions with an overall low agricultural dependence. All of the above suggests a relatively low vulnerability to environmental stressors and, hence, a reduced need to take action in terms of coping and adaptation. In addition, the environmental change processes reported in these studies were mostly related to perceived gradual changes in temperature and rainfall patterns, which were addressed by farmers—if at all—by using *in-situ* adaptation responses, such as modifications in farming practices (e.g. Gbetibouo *et al* 2010, in South Africa; Tambo and Abdoulaye 2013, in Nigeria). Migration as an adaptation strategy was rarely reported. While again only few of the considered communities show this adaptation pattern, it is worthwhile to emphasize that there are also communities in the surveyed sub-Saharan drylands that have no need to adapt to environmental changes, either because of a limited exposure to stressors or reduced susceptibility to their impacts.

The different combinations of strategies used by the five clusters shows the diversity of adaptation approaches in sub-Saharan drylands. Despite this diversity between clusters, similarities can be found for communities belonging to the same cluster. Common adaptation patterns exist, where households are found to employ a combination of certain complementary strategies to adapt to environmental changes. Our indicative findings suggest that these patterns vary by the socioeconomic conditions faced by the populations and possibly also the nature of the environmental change experienced. While a more rigorous analysis of contextual influences is challenging here given the limited scope of our data, we believe that a more careful exploration of these impacts and their role for the evolution of adaptation patterns would be a fruitful direction for future research.

5. Discussion

As our analysis underlines, migration is only one of many potential responses to environmental change and needs to be considered in the broader context of other coping and adaptation strategies, including potential *in-situ* adaptation alternatives (Kniveton *et al* 2011, Gharad *et al* 2014, Cattaneo *et al* 2019). The most common strategies adopted by rural households relate to crop and livestock management. Migration is relevant, but usually does not rank first. Furthermore, our results indicate that while migration is an important strategy in some of the considered communities, it is not common in others.

There is no determinism linking environmental change and migration and not everyone affected is able to or desires to move (Wiederkehr *et al* 2018). Instead, a range of other factors come into play shaping adaptation processes and migration responses to environmental stress, including local agricultural conditions (Feng *et al* 2010, Schlenker and Lobell 2010, Bohra-Mishra *et al* 2017), adaptive capacities (Bardsley and Hugo 2010, Vinke *et al* 2020) and possibilities for income diversification (Mertz *et al* 2009b, Garcia *et al* 2015). While some households in a community may change their mobility behavior, others remain immobile, either because they do not want to move, have no incentive or motivation to do so, or are restricted in their mobility. These diverse patterns also underline yet again the inaccuracy of simplistic and alarmist narratives of mass migration due to climate change (Boas *et al* 2019).

The cluster analysis results, which bring together a large amount of empirical case study insights and external demographic and socioeconomic data, indicate that households use migration as an adaptation strategy in situations of both high and low social and ecological vulnerability. This shows that migration may occur due to high migration pressure resulting from a high environmental risk level and lack of alternatives, but may also be a proactive choice by better-off and less exposed households. It is crucial to bear in mind that, depending on the respective context, migration can take different forms in terms of distance, time frame, level of agency and outcomes. While the case studies highlight the important role of temporary internal migration and seasonal moves as common mobility patterns, there is considerable diversity with households in some communities engaging in international and more permanent forms of migration (e.g. Mersha and Van Laerhoven 2016). In communities characterized by already mobile lifestyles, such as pastoralists, changes in mobility patterns are a common way to respond to environmental hazards.

Despite a range of potential benefits ensuing from migration (Tacoli 2009, Ng'ang'a *et al* 2016), scholars also address possible adverse and often

unforeseeable consequences for the migrants themselves, their households, and their communities, such as a weakened local labor force and loss of solidarity (Mertz *et al* 2009a, McKune and Silva 2013, Yaffa 2013, Mersha and Van Laerhoven 2016). Tebboth *et al* (2019) suggest that the level of agency in the migration decision has a decisive impact on the resilience of households. However, there is still a need to better understand and conceptualize migration as an adaptation strategy to environmental change as well as to define what constitutes socially and ecologically sustainable migration and adaptation for whom (Gemenne and Blocher 2017, Ayeb-Karlsson *et al* 2019, Oakes 2019, Zickgraf 2019). The exploration of different types of migration, their drivers, and outcomes represents an important direction for future research.

The descriptive results indicate that different types of mobility are particularly relevant for (agro-) pastoralist households in sub-Saharan drylands. This may be due to different reasons. Pastoralists are known to be among the most vulnerable population groups. Due to their mobile lifestyle, they are often marginalized, without secure land tenure, difficult to reach with food aid or extension services, and are viewed with suspicion by governments and farmers (Schilling *et al* 2012, Snorek *et al* 2014, López-i-Gelats *et al* 2016). Some studies show that they are generally well adapted to dryland environments and to highly variable rainfall conditions, with mobile herding and transhumance representing a long-term adaptation strategy (e.g. Opiyo *et al* 2015).

However, long agricultural droughts can deplete soil moisture and reduce the availability of natural pastures for grazing livestock, which can lead to livestock loss and can be devastating to pastoralist communities. Under these conditions, migrating beyond their usual grassing lands might be the only viable strategy to ensure survival and expose them to additional risks, including conflicts with other groups (Snorek *et al* 2014). Given their already mobile livelihoods, the threshold for engaging in migration rather than *in-situ* strategies might be lower for pastoralists than for farmers whose cultural identities are closely connected to their land and agricultural activities (Devine-Wright and Quinn 2020).

Different forms of hazards have differential implications for local livelihoods and require different forms of adaptation (Gemenne 2011, Black *et al* 2011a). Local contexts and conditions strongly shape what constitutes an environmental hazard and influence inter-dependencies with other factors. Migration impacts are typically non-linear with hazards affecting migration only after reaching a certain threshold beyond which the pressures become too strong for the system to resist or adapt (Schlenker and Roberts 2009, Burke *et al* 2015, McLeman 2018). Studying environmental impacts on migration hence requires a contextual understanding of local

conditions and how they affect households' capabilities to respond to changing environmental conditions. As we show, migration appears to be particularly important in land degradation contexts, which are also often simultaneously affected by other hazards such as droughts or floods. However, why—or rather how—remains largely unclear (e.g. does it trigger certain migration types? Is it a strategy applied after *in-situ* measures to conserve and restore soils have failed?). In contrast to climatic and socio-economic migration drivers, the role of land degradation in migration processes still constitutes a major research gap (Hermans and McLeman 2021).

Our study faces different limitations which are important for the interpretation of our results. Given that this review is based on the published scientific and English-speaking literature, a certain level of publication bias needs to be acknowledged. Focusing on a narrower set of studies allowed us to manage the large scientific evidence base on this topic and to ensure a sufficient level of comparability and quality. The study areas are spatially unequally distributed, meaning that some countries such as Ghana, Ethiopia or South Africa figure prominently in our sample whereas Côte d'Ivoire, Mozambique, or Somalia, amongst others, are not included (see also Hendrix 2017, Piguet *et al* 2018). Moreover, the predominant focus on small-holder farmers in the literature on responses to climate change and variability in SSA means that fewer data are available on herder communities (see also Shackleton *et al* 2015).

Due to limitations in the reporting of the original studies, we were not able to draw a clear distinction between whether households in a community used a specific activity as a shorter-term coping response to a threat, or as a longer-term adaptation strategy (see also Wiederkehr *et al* 2018). Moreover, the majority of studies considered here does not report whether households were successful in addressing the respective challenges by employing a certain strategy. Also, while the surveyed studies focus on a range of coping and adaptation behaviors, several activities may have gone unnoticed by the researchers because of selected interests and prioritizations in the studies, a stigmatization of certain activities, and underreporting.

Our analysis was carried out at an aggregated meta-analytical level and hence does not allow us to further study the underlying mechanisms and to derive causal conclusions. A more careful exploration of some of the processes at more granular levels would be useful. For example, while we see patterns showing up in our cluster analysis pointing towards certain forms of migration being more dominant in a cluster, we are unable to clearly point to the concrete conditions and migration motivations faced by the households within each cluster. In addition, some of the used data are noisy, for example when it comes to determining the exact

geographic location of communities, which is especially challenging for mobile nomadic communities. Despite of the explorative character of our analysis, it provides a comprehensive overview of central findings in the literature and yields important insights into the role environmental changes and adaptation play for migration and the importance of contextual influences in shaping the processes.

6. Conclusion

Drawing from comprehensive empirical data from 89 case studies covering more than 21 thousand rural households, our review study illustrates the diversity of ways communities in sub-Saharan drylands deal with environmental change and hazards. Measures related to agricultural and livestock management were identified as most common, followed by migration, income diversification, and soil and water conservation. Most importantly, our findings show that the relevance of migration as adaptation strategy depends on the respective livelihood and ecological context. Migration was found to be more prominent among (agro-)pastoralists than farming households, and was reported most often in the context of rainfall variability, land degradation, droughts and floods.

Our results indicate that migration is closely linked to and complemented by other strategies, in particular livestock-related forms of adaptation, the diversification of income sources, the search for social support, and changes in food provision and consumption. This corroborates that a holistic perspective, which considers migration in connection with other adaptation strategies, is indispensable to advance research on environmental migration. Our cluster analysis reveals three distinct migration clusters shaped by different socioeconomic profiles and varying levels of vulnerability. This confirms that environmental migration occurs in contexts of both low and high social and ecological vulnerability. In other words, depending on the circumstances, migration can be a strategy of last resort due to high environmental stress and lacking *in-situ* alternatives or a proactive choice of individuals and households with potential positive synergy effects with other strategies, increasing household resilience.

Policy interventions should generally be designed to increase the agency of vulnerable population groups and aim to facilitate movement of those who wish to migrate and to assist *in-situ* adaptation of those who wish to stay. Empowering households exposed to environmental risks to take self-determined decisions will be key to increase the adaptive and beneficial potential of migration. Moreover, our results underline the necessity of carefully tailoring policy measures to the respective livelihood and ecological context given the range of situational needs and household capacities. Migration as

an adaptation strategy itself is embedded in a range of other activities carried out by households that should likewise be a focus of holistic policy responses to changing environmental conditions. Climate change will have major implications for drylands in SSA. The development of foresighted and anticipatory policy instruments and the strengthening of the adaptive capacities and capabilities of vulnerable populations are hence key to prevent and mitigate negative impacts in the future (Gemenne and Blocher 2017, Cattaneo *et al* 2019).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors. The full list of studies considered in this review are displaced in supplementary table S1.

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References

- Ansah I G K, Gardebroek C and Ihle R 2020 Shock interactions, coping strategy choices and household food security *Clim. Dev.* **13** 1–13
- Antwi-Agyei P, Stringer L C and Dougill A J 2014 Livelihood adaptations to climate variability: insights from farming households in Ghana *Reg. Environ. Change* **14** 1615–26
- Ariti A T, van Vliet J and Verburg P H 2015 Land-use and land-cover changes in the Central Rift Valley of Ethiopia: assessment of perception and adaptation of stakeholders *Appl. Geogr.* **65** 28–37

- Ayeb-Karlsson S, Kniveton D, Cannon T, Geest K V D, Ahmed I, Derrington E M, Florano E and Opondo D O 2019 I will not go, I cannot go: cultural and social limitations of disaster preparedness in Asia, Africa, and Oceania *Disasters* **43** 752–70
- Barbier B, Yacouba H, Karambiri H, Zoromé M and Somé B 2009 Human vulnerability to climate variability in the Sahel: farmers' adaptation strategies in northern Burkina Faso *Environ. Manage.* **43** 790–803
- Bardsley D K and Hugo G J 2010 Migration and climate change: examining thresholds of change to guide effective adaptation decision-making *Popul. Environ.* **32** 238–62
- Basupi L V, Quinn C H and Dougill A J 2019 Adaptation strategies to environmental and policy change in semi-arid pastoral landscapes: evidence from Ngamiland, Botswana *J. Arid Environ.* **166** 17–27
- Beine M and Jeusette L 2021 A meta-analysis of the literature on climate change and migration *J. Demogr. Econ.* **87** 293–344
- Berhanu W and Beyene F 2015 Climate variability and household adaptation strategies in Southern Ethiopia *Sustainability* **7** 6353–75
- Berrang-Ford L, Ford J D and Paterson J 2011 Are we adapting to climate change? *Glob. Environ. Change* **21** 25–33
- Black R, Adger W N, Arnell N W, Dercon S, Geddes A and Thomas D 2011a The effect of environmental change on human migration *Glob. Environ. Change* **21** 3–11
- Black R, Stephen R, Bennett G, Thomas S M and Beddington J R 2011b Migration as adaptation *Nature* **478** 447–9
- Boas I et al 2019 Climate migration myths *Nat. Clim. Change* **9** 901–3
- Bohra-Mishra P, Oppenheimer M, Cai R, Feng S and Licker R 2017 Climate variability and migration in the Philippines *Popul. Environ.* **38** 286–308
- Bola G, Mabiza C, Goldin J, Kujinga K, Nhapi I, Makurira H and Mashauri D 2014 Coping with droughts and floods: a case study of Kanyemba, Mbire District, Zimbabwe *Phys. Chem. Earth* **67–69** 180–6
- Borderon M, Sakdapolrak P, Muttarak R, Kebede E, Pagnogna R and Sporer E 2019 Migration influenced by environmental change in Africa: a systematic review of empirical evidence *Demogr. Res.* **11** 491–544
- Brottem L V 2016 Environmental change and farmer-herder conflict in Agro-Pastoral West Africa *Hum. Ecol.* **44** 547–63
- Burke M, Hsiang S M and Miguel E 2015 Global non-linear effect of temperature on economic production *Nature* **527** 235–9
- Carter M, Little P, Mogue T and Negatu W 2005 Shocks, sensitivity and resilience: tracking the economic impacts of environmental disaster on assets in Ethiopia and Honduras (Dev. Comp Syst.)
- Cattaneo C, Beine M, Fröhlich C J, Kniveton D, Martinez-Zarzoso I, Mastrotillo M, Millock K, Piguet E and Schraven B 2019 Human migration in the era of climate change *Rev. Environ. Econ. Policy* **13** 189–206
- Cattaneo C and Peri G 2016 The migration response to increasing temperatures *J. Dev. Econ.* **122** 127–46
- Cervigni R and Morris M 2016 *Confronting Drought in Africa's Drylands: Opportunities for Enhancing Resilience* (Washington, DC: World Bank)
- Chianu J N, Tsujii H and Kormawa P 2004 Agriculture in the savannas of northern Nigeria. Pressures, transformations, damage and coping strategies *Outlook Agric.* **33** 247–53
- Clement V, Rigaud K K, de Sherbinin A, Jones B, Adamo S, Schewe J, Sadiq N and Shabahat E 2021 *Groundswell Part 2: Acting on Internal Climate Migration* (Washington, DC: World Bank)
- Connolly-Boutin L and Smit B 2016 Climate change, food security, and livelihoods in sub-Saharan Africa *Reg. Environ. Change* **16** 385–99
- CRED 2022 EM-DAT: the emergency events database (Centre for Research on the Epidemiology of Disasters) (available at: www.emdat.be) (Accessed 30 April 2022)
- Devine-Wright P and Quinn T 2020 Dynamics of place attachment in a climate changed world *Place Attachment* ed L C Manzo and P Devine-Wright (London: Routledge) pp 226–42
- Diffenbaugh N S et al 2017 Quantifying the influence of global warming on unprecedented extreme climate events *Proc. Natl Acad. Sci. USA* **114** 4881–6
- Dow K, Berkhout F and Preston B L 2013 Limits to adaptation to climate change: a risk approach *Curr. Opin. Environ. Sustain.* **5** 384–91
- Dumenu W K and Obeng E A 2016 Climate change and rural communities in Ghana: social vulnerability, impacts, adaptations and policy implications *Environ. Sci. Policy* **55** 208–17
- Eriksen S H, Brown K and Kelly P M 2005 The dynamics of vulnerability: locating coping strategies in Kenya and Tanzania *Geogr. J.* **171** 287–305
- Falco C, Galeotti M and Olper A 2019 Climate change and migration: is agriculture the main channel? *Glob. Environ. Change* **59** 101995
- Fankhauser S 2017 Adaptation to Climate Change *Annu. Rev. Resour. Econ.* **9** 209–30
- FAO, IFAD, UNICEF 2019 *The State of Food Security and Nutrition in the World. Safeguarding against Economic Slowdowns and Downturns* (Rome: FAO)
- FAO 2018 Pastoralism in Africa's drylands: reducing risks, addressing vulnerability and enhancing resilience (Rome: FAO)
- FAO 2019 Trees, forests and land use in drylands: the first global assessment, Food and Agriculture Organization of the United Nations *Forestry Paper* No. 184 (Rome)
- Feng S, Krueger A B and Oppenheimer M 2010 Linkages among climate change, crop yields and Mexico—US cross-border migration *Proc. Natl Acad. Sci.* **107** 14257–62
- Fjelde H and von Uexkull N 2012 Climate triggers: rainfall anomalies, vulnerability and communal conflict in sub-Saharan Africa *Polit. Geogr.* **31** 444–53
- Foresight 2011 *Migration and Global Environmental Change: Future Challenges and Opportunities* (London: The Government Office for Science)
- Garcia A J, Pindolia D K, Lopiano K K and Tatem A J 2015 Modeling internal migration flows in sub-Saharan Africa using census microdata *Migr. Stud.* **3** 89–110
- Gbetibouo G A, Hassan R M and Ringler C 2010 Modelling farmers' adaptation strategies for climate change and variability: the case of the Limpopo basin, South Africa *Agrekon* **49** 217–34
- Gebrehiwot T and van der Veen A 2013 Farm level adaptation to climate change: the case of farmer's in the Ethiopian highlands *Environ. Manage.* **52** 29–44
- Gemenne F 2011 Why the numbers don't add up: a review of estimates and predictions of people displaced by environmental changes *Glob. Environ. Change* **21** 41–49
- Gemenne F and Blocher J 2017 How can migration serve adaptation to climate change? Challenges to fleshing out a policy ideal *Geogr. J.* **183** 336–47
- Gharad B, Chowdhury S and Mobarak A M 2014 Underinvestment in a profitable technology: the case of seasonal migration in Bangladesh *Econometrica* **82** 1671–748
- Hänke H, Barkmann J, Coral C, Enforskaustky E and Marggraf R 2017 Social-ecological traps hinder rural development in Southwestern Madagascar *Ecol. Soc.* **22** 42
- Harris I, Osborn T J, Jones P and Lister D 2020 Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset *Sci. Data* **7** 1–18
- Hartigan J A and Wong M A 1979 Algorithm AS 136: a K-means clustering algorithm *Appl. Stat.* **28** 100
- Hendrix C S 2017 The streetlight effect in climate change research on Africa *Glob. Environ. Change* **43** 137–47
- Hermans K and Garbe L 2019 Droughts, livelihoods, and human migration in northern Ethiopia *Reg. Environ. Change* **19** 1101–11
- Hermans K and McLeman R 2021 Climate change, drought, land degradation and migration: exploring the linkages *Curr. Opin. Environ. Sustain.* **50** 236–44

- Hoffmann R 2022 Contextualizing climate change impacts on human mobility in African drylands *Earths Future* **10** e2021EF002591
- Hoffmann R, Dimitrova A, Mutarak R, Crespo Cuaresma J and Peisker J 2020 A meta-analysis of country level studies on environmental change and migration *Nat. Clim. Change* **10** 904–12
- Hoffmann R and Mutarak R 2021 *Environment, Migration and Urbanisation: Challenges and Solutions for Low- and Middle-Income Countries* (T20 Task Force on Migration)
- Hoffmann R, Šedová B and Vinke K 2021 Improving the evidence base on climate migration: methodological insights from two meta-analyses *Glob. Environ. Change* **71** 102367
- Hooli L J 2016 Resilience of the poorest: coping strategies and indigenous knowledge of living with the floods in Northern Namibia *Reg. Environ. Change* **16** 695–707
- Hoover D L, Bestelmeyer B, Grimm N B, Huxman T E, Reed S C, Sala O, Seastedt T R, Wilmer H and Ferrenberg S 2020 Traversing the wasteland: a framework for assessing ecological threats to drylands *Bioscience* **70** 35–47
- Huang J, Yu H, Guan X, Wang G and Guo R 2016 Accelerated dryland expansion under climate change *Nat. Clim. Change* **6** 166–71
- Huho J M, Ngaira J K W and Ogindo H 2011 Living with drought: the case of the Maasai pastoralists of northern Kenya *Educ. Res.* **2** 779–89
- Hunter L M, Luna J K and Norton R M 2015 Environmental dimensions of migration *Annu. Rev. Sociol.* **41** 377–97
- IPCC 2018 *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* ed V Masson-Delmotte et al (Cambridge: Cambridge University Press)
- IPCC 2019 *Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* ed P R Shukla et al (Cambridge: Cambridge University Press)
- IPCC 2022 *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed H-O Pörtner et al (Cambridge University Press) accepted
- Jacobson C, Crevello S, Chea C and Jarihani B 2019 When is migration a maladaptive response to climate change? *Reg. Environ. Change* **19** 101–12
- Kniveton D, Black R and Schmidt-Verkerk K 2011 Migration and climate change: towards an integrated assessment of sensitivity *Environ. Plan. A* **43** 431–50
- Koubi V, Spilker G, Schaffer L and Böhmelt T 2016 The role of environmental perceptions in migration decision-making: evidence from both migrants and non-migrants in five developing countries *Popul. Environ.* **38** 134–63
- Kumasi T C, Antwi-Agyei P and Obiri-Danso K 2019 Small-holder farmers' climate change adaptation practices in the Upper East Region of Ghana *Environ. Dev. Sustain.* **21** 745–62
- López-i-Gelats F, Fraser E D G, Morton J F and Rivera-Ferre M G 2016 What drives the vulnerability of pastoralists to global environmental change? A qualitative meta-analysis *Glob. Environ. Change* **39** 258–74
- Maechler M et al 2021 R package 'cluster' (CRAN Repos) (available at: <https://cran.r-project.org/web/packages/cluster/index.html>)
- McKune S L and Silva J A 2013 Pastoralists under pressure: double exposure to economic and environmental change in Niger *J. Dev. Stud.* **49** 1711–27
- McLeman R 2018 Thresholds in climate migration *Popul. Environ.* **39** 319–38
- McLeman R and Smit B 2006 Migration as an adaptation to climate change *Clim. Change* **76** 31–53
- Mersha A A and Van Laerhoven F 2016 A gender approach to understanding the differentiated impact of barriers to adaptation: responses to climate change in rural Ethiopia *Reg. Environ. Change* **16** 1701–13
- Mertz O, D'haen S, Maiga A, Moussa I B, Barbier B, Diouf A, Diallo D, Dapola Da E and Dabi D 2012 Climate variability and environmental stress in the Sudan-Sahel zone of West Africa *Ambio* **41** 380–92
- Mertz O, Halsnæs K, Olesen J E and Rasmussen K 2009a Adaptation to climate change in developing countries *Environ. Manag.* **43** 743–52
- Mertz O, Mbow C, Reenberg A and Diouf A 2009b Farmers' perceptions of climate change and agricultural adaptation strategies in rural Sahel *Environ. Manag.* **43** 804–16
- Middleton N and Sternberg T 2013 Climate hazards in drylands: a review *Earth-Sci. Rev.* **126** 48–57
- Middleton N, Stringer L C and Thomas D 2011 *The Forgotten Billion: MDG Achievement in the Drylands* (New York: UNDP)
- Mogotsi K, Nyangito M M and Nyariki D M 2013 The role of drought among agro-pastoral communities in a semi-arid environment: the case of Botswana *J. Arid Environ.* **91** 38–44
- Motsholapheko M R, Vanderpost C and Kgathi D L 2012 Rural livelihoods and household adaptation to desiccation in the Okavango Delta, Botswana *J. Water Clim. Change* **3** 300–16
- Mubaya C P and Mafongoya P 2017 Local-level climate change adaptation decision-making and livelihoods in semi-arid areas in Zimbabwe *Environ. Dev. Sustain.* **19** 2377–403
- Ng'ang'a S K, van Wijk M T, Rufino M C and Giller K E 2016 Adaptation of agriculture to climate change in semi-arid Borena, Ethiopia *Reg. Environ. Change* **16** 2317–30
- Ngwese N M, Saito O, Sato A, Bofo Y A and Jasaw G 2018 Traditional and local knowledge practices for disaster risk reduction in Northern Ghana *Sustainability* **10** 825
- Oakes R 2019 Culture, climate change and mobility decisions in Pacific Small Island Developing States *Popul. Environ.* **40** 480–503
- Okpara U T, Stringer L C and Dougill A J 2016 Lake drying and livelihood dynamics in Lake Chad: unravelling the mechanisms, contexts and responses *Ambio* **45** 781–95
- Opiyo F, Wasonga O, Nyangito M, Schilling J and Munang R 2015 Drought adaptation and coping strategies among the Turkana pastoralists of Northern Kenya *Int. J. Disaster Risk Sci.* **6** 295–309
- Osbaer H, Twyman C, Adger W N and Thomas D S G 2010 Evaluating successful livelihood adaptation to climate variability and change in Southern Africa *Ecol. Soc.* **15** 22
- Oyerinde G T, Hountondji F C C, Wisser D, Diekkrüger B, Lawin A E, Odofin A J and Afouda A 2015 Hydro-climatic changes in the Niger basin and consistency of local perceptions *Reg. Environ. Change* **15** 1627–37
- Padonou E A, Fandohan B, Bachmann Y and Sinsin B 2014 How farmers perceive and cope with bowalization: a case study from West Africa *Land Use Policy* **36** 461–7
- Pauline N M, Vogel C, Grab S and Liwenga E T 2017 Smallholder farmers in the Great Ruaha River sub-Basin of Tanzania: coping or adapting to rainfall variability? *Clim. Dev.* **9** 217–30
- Perch-Nielsen S L, Bättig M B and Imboden D 2008 Exploring the link between climate change and migration *Clim. Change* **91** 375–93
- Pigué E 2010 Linking climate change, environmental degradation, and migration: a methodological overview *Wiley Interdiscip. Rev. Clim. Change* **1** 517–24
- Pigué E, Kaenzig R and Guélat J 2018 The uneven geography of research on 'environmental migration' *Popul. Environ.* **39** 357–83
- Rasmussen L V 2018 Re-defining Sahelian 'adaptive agriculture' when implemented locally: beyond techno-fix solutions *World Dev.* **108** 274–82
- Safriel U et al 2005 Dryland systems *Ecosystems and Human Well-being: Current State and Trends. Findings of the Condition and Trends Working Group* vol 1, ed R Hassan,

- R Scholes and N Ash (Washington, DC: Island Press) ch 22, pp 623–62
- Schilling J, Opiyo F E and Scheffran J 2012 Raiding pastoral livelihoods: motives and effects of violent conflict in north-western Kenya *Res. Policy Pract.* **2** 1–16
- Schlenker W and Lobell D B 2010 Robust negative impacts of climate change on African agriculture *Environ. Res. Lett.* **5** 014010
- Schlenker W and Roberts M J 2009 Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change *Proc. Natl Acad. Sci.* **106** 15594–8
- Šedová B, Cizmaziová L and Cook A 2021 A meta-analysis of climate migration literature *CEPA Discussion Papers* 29 (Center for Economic Policy Analysis)
- Shackleton S, Ziervogel G, Sallu S, Gill T and Tschakert P 2015 Why is socially-just climate change adaptation in sub-Saharan Africa so challenging? A review of barriers identified from empirical cases *Wiley Interdiscip. Rev. Clim. Change* **6** 321–44
- Shiferaw B, Tesfaye K, Kassie M, Abate T, Prasanna B M and Menkir A 2014 Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: technological, institutional and policy options *Weather Clim. Extrem.* **3** 67–79
- Silvestri S, Bryan E, Ringler C, Herrero M and Okoba B 2012 Climate change perception and adaptation of agro-pastoral communities in Kenya *Reg. Environ. Change* **12** 791–802
- Smucker T A and Wisner B 2008 Changing household responses to drought in Tharaka, Kenya: vulnerability, persistence and challenge *Disasters* **32** 190–215
- Snorek J, Renaud F G and Kloos J 2014 Divergent adaptation to climate variability: a case study of pastoral and agricultural societies in Niger *Glob. Environ. Change* **29** 371–86
- Tacoli C 2009 Crisis or adaptation? Migration and climate change in a context of high mobility *Environ. Urban.* **21** 513–25
- Tambo J A 2016 Adaptation and resilience to climate change and variability in north-east Ghana *Int. J. Disaster Risk Reduct.* **17** 85–94
- Tambo J A and Abdoulaye T 2013 Smallholder farmers' perceptions of and adaptations to climate change in the Nigerian savanna *Reg. Environ. Change* **13** 375–88
- Tebboth M G L, Conway D and Adger W N 2019 Mobility endowment and entitlements mediate resilience in rural livelihood systems *Glob. Environ. Change* **54** 172–83
- Tesfaye W and Seifu L 2016 Climate change perception and choice of adaptation strategies: empirical evidence from smallholder farmers in east Ethiopia *Int. J. Clim. Change Strateg. Manage.* **8** 253–70
- Thornton P K, Jones P G, Ericksen P J and Challinor A J 2011 Agriculture and food systems in sub-Saharan Africa in a 4 °C+ world *Phil. Trans. R. Soc. A* **369** 117–36
- Tongruksawattana S and Wainaina P 2019 Climate shock adaptation for Kenyan maize-legume farmers: choice, complementarities and substitutions between strategies *Clim. Dev.* **11** 710–22
- UNEP-WCMC 2007 A spatial analysis approach to the global delineation of dryland areas of relevance to the CBD programme of work on dry and subhumid lands. Dataset based on spatial analysis between WWF terrestrial ecoregions (WWF-US, 2004) and aridity zones (CRU/UEA; UNEPGRID, 1991). Dataset checked and refined to remove many gaps, overlaps and slivers (July 2014)
- UNEP 2011 *Livelihood Security: Climate Change, Migration and Conflict in the Sahel* (Nairobi: UNEP)
- United Nations Economic and Social Council 2007 Africa review report on drought and desertification
- Vinke K, Bergmann J, Blocher J, Upadhyay H and Hoffmann R 2020 Migration as adaptation? *Migr. Stud.* **8** 626–34
- Warner K, Geest K V D, Kreft S, Huq S, Harmeling S, Kusters K and Sherbinin A D 2012 Evidence from the frontlines of climate change: loss and damage to communities despite coping and adaptation, loss and damage in vulnerable countries initiative *Policy Report* Report No. 9 (Bonn)
- Wiederkehr C, Beckmann M and Hermans K 2018 Environmental change, adaptation strategies and the relevance of migration in sub-Saharan drylands *Environ. Res. Lett.* **13** 113003
- Wuepper D, Yesigat Ayenew H and Sauer J 2018 Social capital, income diversification and climate change adaptation: panel data evidence from rural Ethiopia *J. Agric. Econ.* **69** 458–75
- Xu C, Kohler T A, Lenton T M, Svenning J-C and Scheffer M 2020 Future of the human climate niche *Proc. Natl Acad. Sci. USA* **117** 1–6
- Yaffa S 2013 Coping measures not enough to avoid loss and damage from drought in the North Bank Region of the Gambia *Int. J. Glob. Warm.* **5** 467–82
- Yila J O and Resurreccion B P 2014 Gender perspectives on agricultural adaptation to climate change in drought-prone Nguru local government area in the semiarid zone of northeastern Nigeria *Int. J. Clim. Change Strateg. Manage.* **6** 250–71
- Zampaligré N, Dossa L H and Schlecht E 2014 Climate change and variability: perception and adaptation strategies of pastoralists and agro-pastoralists across different zones of Burkina Faso *Reg. Environ. Change* **14** 769–83
- Zickgraf C 2019 Keeping people in place: political factors of (im)mobility and climate change *Soc. Sci.* **8** 1–17