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Environmental drivers of human migration in drylands — A spatial picture

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ABSTRACT

It is widely accepted that environmental change can influence human migration. In particular, the environment plays a role in migration processes in drylands, in which environmental change—including increasing variability of rainfall, increasing frequency of droughts, chronic water shortage, and land degradation—can heavily influence migration. However, systematic large-scale studies of the relationship between environmental factors and human migration are rare, and a global, consistent picture of environmental drivers of migration is lacking. In this study, we sought to fill this gap by analysing spatial patterns of environmental drivers of migration in drylands by performing a cluster analysis on spatially explicit global data. In this analysis, we focused explicitly on precipitation, aridity, drought, land degradation, soil constraints, and availability of cropland and pastures as potential environmental drivers of migration in drylands. In addition, we linked the identified clusters to two observed hotspots of out-migration—Burkina Faso and Northeast Brazil—to gauge the cluster results. Our results show that environmental drivers can be grouped into eight distinct clusters, and we identified the most severe environmental constraints for each cluster. These results suggest that out-migration—both in absolute and relative terms—occurs most frequently in a cluster that is constrained primarily by land degradation rather than water availability.

Introduction

It is generally accepted that environmental change can influence human migration (Foresight, 2011; Adger et al., 2014); this process is called environment-induced migration. In drylands, migration is a commonly used strategy to cope with environmental change, as the natural resource base—which is highly susceptible to climate change—largely determines the livelihood of rural populations. Drylands cover approximately 40% of the Earth's land surface and has more than 2 billion inhabitants, 90% of whom are located in developing countries (IIED, 2008). Today, more than half of the world's impoverished live in drylands (IIED, 2008; Safriel & Adeel, 2005). Hunger- and poverty-related vulnerability are likely to increase in drylands as a result of environmental changes such as land degradation, increasing variability of rainfall, chronic water shortage, and an increasing frequency of droughts (IIED, 2008; Sissoko, Keulen, Verhagen, Tekken, & Battaglini, 2011; van der Geest & Dietz, 2004). These environmental changes are recognized as potential drivers of out-migration and are acknowledged to contribute to the migration of large numbers of people (Foresight, 2011; IOM, 2008a).

Since the 1980s, after a period of neglect, the interest in migration-driving environmental factors has been growing (Piguet, 2012). Recently, an increasing number of scholars used theoretical frameworks to acknowledge the complex role that environmental change plays in migration processes (Black et al., 2011; McLeman & Smit, 2006; Perch-Nielsen, Bättig, & Imboden, 2008). These frameworks extend beyond the simple assumption that adverse environmental conditions straightforwardly cause migration. Moreover, a growing number of case studies illustrate that migration can be a valuable climate adaptation strategy to improve

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livelihoods in drylands (Brockhaus, Djoudi, & Locatelli, 2013; McLeman & Hunter, 2010; McLeman & Smit, 2006; Meze-Hausken, 2000; Roncoli, Ingram, & Kirshen, 2001; Scheffran, Marmer, & Sow, 2012). However, analytical and spatially explicit studies regarding the interaction between environmental change and human migration are relatively rare. Studies that empirically explore relationships between environmental pressure and human migration in drylands are typically restricted to particular stress factors in selected regions, for example, droughts in Ethiopia (Gray & Müller, 2012), vegetation changes in Ghana (Van der Geest, Vrieling, & Dietz, 2010), or changes in rainfall patterns in Burkina Faso (Henry, Schoumaker, & Beauchemin, 2004). However, there is a general paucity of integrated analyses of the interplay between multiple environmental pressures and human migration at the macro-scale. Moreover, systematic large-scale projects that employ a consistent and comparable approach at several sites are rare and meta-studies are virtually missing (Piguet, Pécoud, & de Guchteneire, 2011). In addition, there is a lack of insight regarding the mechanisms that lead to environment-induced migration. As a result, no globally consistent picture of the environmental drivers of human migration in drylands has emerged.

Given the caveat that environmental factors are only one of many factors that can potentially drive migration, here we present a global-scale approach used to analyse spatial patterns of environmental drivers of human migration in drylands, and we link these drivers to observed hotspots of out-migration. To achieve this objective, we applied a cluster analysis to spatially explicit global data (Janssen, Walther, & Lüdeke, 2012). Cluster analysis is a commonly used statistical method to classify observations based on their similarity. Our results reveal that environmental constraints in drylands can be grouped into eight distinct clusters, and the most distinctive indicators are related to water and land availability. These clusters can be used to better characterise regions of out-migration in drylands and to understand some of the dynamics that underlie out-migration.

Drivers of migration

A broad range of terms and concepts are generally used to classify migration that results from environmental factors (IOM, 2008b). These concepts all draw on the classical migration theory of push and pull factors (Lee, 1966) by assigning relatively high importance to push factors that are linked to environmental conditions at the place of origin. However, environmental change is rarely the sole cause of out-migration, as migration usually occurs in a broader socio-economic and political context. If—and how—environmental change triggers migration can also depend on political, economic, and demographic constraints at various scales; therefore, measuring and isolating 'pure' environment-induced migration and making generalisation regarding the causes and consequences of migration is challenging (Black et al., 2011; De Haas, 2010; Richmond, 1995; Suhrke, 1993). Consequently, estimates of the current and future numbers of environmental migrants vary widely (Gemenne, 2011). Moreover, the individual's expectations with respect to the benefits of migration—as well as the resulting financial and psychological costs—can affect the individual's decision whether to migrate or not. Here, we focus on migration that is linked to a gradual decline in environmental conditions within the context of population growth, low agricultural productivity, poverty, and fragile ecosystems (IOM, 2008b).

Building on the work of Black et al. (2011), we distinguished the following six interrelated categories of macro-level drivers of migration in drylands: political factors, demographic factors, economic factors, social factor, environmental factors, and food security (Fig. 1). Nevertheless, in our analysis, we only account for environmental drivers, as reliable global grid cell data regarding the other categories of drivers in drylands are scarce. Political drivers of migration include governance types, conflicts, security, discrimination, and persecution as well as formalised resettlement programmes and/or policies. Economic drivers include technological development, investments, employment opportunities, income levels, and market integration. Economic and political drivers interact at various levels; for example, large-scale infrastructure programmes designed to stimulate economic development usually fall under the umbrella of national or sub-national government-based strategic development programmes and policies. Although economic development often attracts immigrants, it is usually impossible to attribute the resulting in-migration solely to either political or economic factors, as these factors are usually closely related. In contrast, an economic crisis can trigger political instability, thereby potentially causing a change in the political system and possible out-migration. Demographic drivers include population structure, growth, and the occurrence of diseases, all of which can depend strongly on the economic and/or political context. For example, to successfully curtail diseases such as malaria and HIV, providing health education programmes and access to medical care is essential. Typically, such programmes are part of—or are excluded from—the national health policy, which illustrates the tight relationship between demographic and political drivers. Furthermore, demographic drivers can determine economic development via mechanisms such as education, labour availability, and labour force. Environmental drivers of migration include *rapid-onset* changes (such as floods and hurricanes) as well as *slow-onset* changes, which include land degradation, desertification, and changes in climate variability. Both the severity and frequency of such environmental drivers are likely to be affected by global environmental change, which is considered to be—at least in part—a consequence of complex socio-economic changes that have been developing for decades. Food security is closely related to the other four categories of drivers (political, demographic, economic, and environmental) and plays a central role in migration. Therefore, food security is a function of agricultural production, investments in food production technologies, infrastructure for food storage and distribution, population pressure, trade policies, food prices, and political stability. The perceived and actual differences between the place of origin and the destination with respect to one or more of the illustrated drivers can influence whether people choose to migrate or not. In addition, social factors—including family obligations, culture, and access to migration networks—can influence an individual's decision of whether or not to migrate.

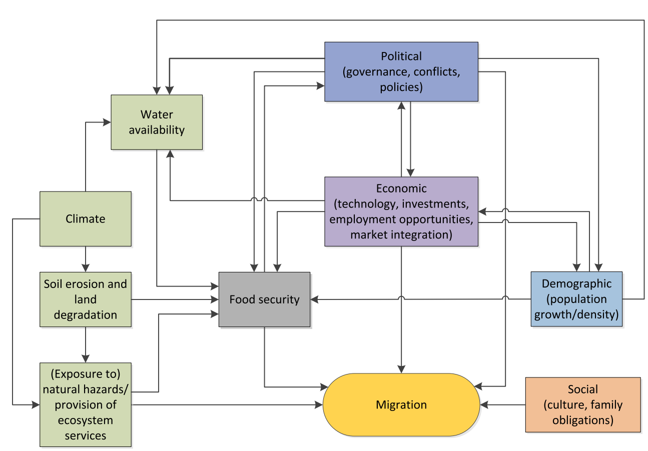

Fig. 1. Drivers of migration in drylands. Based on the scope of this study, the environmental drivers are described in more detail than the other drivers.

Data and methods

Environmental drivers

In our statistical analysis, we explicitly focussed on environmental drivers of migration, given the limited availability of global grid cell data regarding non-environmental drivers. We used spatially explicit information of potential environmental drivers of out-migration. Based on Fig. 1, we selected the following seven indicators (these indicators are elaborated below): annual mean precipitation, aridity, drought frequency, land degradation, soil constraints, cropland, and pasture area (Table 1).

Increasing water scarcity is seen to be a major driver of migration in drylands (McLeman & Hunter, 2010; Mehta, 2007; Meze-Hausken, 2000). Water availability in drylands is determined primarily by the quantity and distribution of precipitation during the crop-growing period and by aridity. To cover the various dimensions of water availability, we included three complementary water-related indicators in our analysis. We used the mean annual precipitation for the year 2000 based on CRU data (Mitchell & Jones, 2005). Precipitation can be used as an indicator of water supply without specifying how much of the precipitation is available for the fauna and flora. To account for the portion of precipitation that is directly available for plants only, precipitation must be corrected for evapotranspiration. This correction is usually performed by relating precipitation to potential evapotranspiration (PET) in order to derive the aridity index. For our analysis, we obtained data regarding global aridity from the CGIAR Consortium (Trabucco & Zomer, 2009), who derived aridity information by integrating monthly mean precipitation data from the CRU together with simulated PET data (Mitchell & Jones, 2005). Because our goal was to focus solely on arid regions, we excluded all dry sub-humid regions (i.e. all regions with an aridity index >0.5) from our analysis. A high aridity index reflects low aridity. Together, the precipitation and aridity indicators reflect the average conditions for the year 2000. To account for long-term variability in the water supply, we calculated a drought frequency indicator for the period 1970 through 2000 to capture changes in annual precipitation variability within a given year. To calculate this indicator, we calculated annual precipitation variability using monthly precipitation data from the CRU (Mitchell & Jones, 2005). Annual precipitation variability is the degree of deviation of the annual value derived from the 31-year mean divided by the 31-year standard deviation (Marchiori, Maystadt, & Schumacher, 2012). Using annual precipitation variability, we determined whether each year was significantly drier or wetter than the other 30 years in the time period. Adding up all of the particularly dry years provided an approximation of drought frequency.

Worldwide, drylands comprise 44% of cultivated land and support 50% of all livestock (UNCCD, 2013). Thus, in addition to water availability, land and soil conditions essentially determine the livelihood of the local population. To represent soil constraints, we used information on soil and terrain limitations from IIASA/FAO (2012). This dataset combines information regarding soil nutrient availability, soil nutrient retention capacity, soil rooting conditions, soil oxygen availability, soil toxicities, soil salinity and sodicity conditions, and soil management constraints in a soil constraints rating. In addition to soil constraints, we also included land degradation, which is often identified as a major driver of increasing vulnerability and human migration in drylands (Grote & Warner, 2010). In addition to climate change, the principal drivers of land degradation include overgrazing, erosion, deforestation, unsustainable agricultural intensification, and urbanisation (Bowyer et al., 2009). In accordance with Bai, Conijn, Bindraban, and Rutgers (2012), we define land degradation as a disturbance-driven, long-term loss of land productivity from which the land cannot recover without assistance. Because land degradation can be measured as the change in net primary productivity (NPP) over time, we used NPP change estimates based on remote-sensing Normalised Difference Vegetation Index (NDVI) time series as a proxy for land degradation (Conijn, Bai, Bindraban, & Rutgers, 2013). The NDVI data are based on fortnightly Advanced Very High Resolution Radiometer (AVHRR) measurements (Tucker, Pinzon, & Brown, 2004) that were aggregated to an annual scale (Bai et al., 2012).

To capture land scarcity and the intensity of agricultural production in our analysis, we used the extent of cropland and pasture land from Ramankutty, Evan, Monfreda, and Foley (2008). These data reflect a complex interplay between issues related to climate, accessibility, and legislation (including property rights and land usability), which together determine whether or not—and the degree to which—a specific plot of land is used for pasture or cropping. In the subsequent analyses, we excluded all grid cells that were covered by ≥75% cropland and for which ≥75% was equipped with irrigation facilities (Siebert et al., 2005; Siebert, Hoogeveen, & Frenken, 2006). For these grid cells, we hypothesised that agricultural production is intense and therefore less vulnerable to adverse environmental conditions relative to the cropland that was included in the analysis. In total, we included approximately 17,000 grid cells with a spatial resolution of 0.5° in our analysis. Prior to our analysis we normalised all indicators to the zero to one range according to their minimum and maximum values among all grid cells to allow for comparability of indicator values (see Eq. (1)).

$$I_{x,\ 0\ \text{to}\ 1} = \frac{I_x - I_{\min}}{I_{\max} - I_{\min}} \tag{1}$$

I = Indicator
x = Grid cell
$I_{x,\ 0\ \text{to}\ 1}$ = Grid cell x normalized to range 0–1
$I_{\min}$ = Minima among all grid cells
$I_{\max}$ = Maxima among all grid cells

Table 1
Description and sources of the data used in the cluster analysis.

Indicator	Description [unit]	Indicator range across all cells	Source
Annual mean precipitation	Annual average for 2000 [mm/day]	0–5	Mitchell & Jones (2005)
Aridity	Ratio of precipitation to potential evapotranspiration for 2000 [index]	0–0.5	Trabucco & Zomer (2009)
Drought frequency	Occurrence of droughts from 1970 through 2000 [frequency]	9–30	Derived from CRU precipitation data (Mitchell & Jones, 2005)
Land degradation	Change in NDVI between 1981 and 2006 [% NPP change]	0–4	Conijn et al. (2013)
Soil constraints	Soil fertility constraints (combining slope, terrain, drainage, texture, and chemical constraints) [index]	1–8	GAEZ 3p0 (http://gaez.fao.org)
Cropland	Cropping area in 2000 [percent per grid cell]	0–75	Ramankutty et al. (2008)
Pasture	Pasture area in 2000 [percent per grid cell]	0–100	Ramankutty et al. (2008)

Cluster analysis

The goal of our study was to describe the spatial pattern of environmental migration incentives at the global level using cluster analyses. Cluster analysis is a statistical method that classifies observations into groups (so-called 'clusters') by calculating similarities amongst all observations using a measure of distance. Observations within a given cluster (intra-cluster observations) are more similar to each other than to observations in other clusters (inter-cluster observations).

To perform the cluster analyses, we used the software environment *R* (see http://cran.r-project.org), a versatile open-source environment with extensive statistical functionality for data analysis, calculation, and graphical display. The cluster analysis was performed in two steps as described by Janssen et al. (2012) to account for (1) effects of initialisation and (2) to select the appropriate number of clusters:

(1) The common *k-means* cluster algorithm was applied to the complete indicator dataset, which consisted of the above-described seven environmental indicators for all dryland grid cells (~17,000 cells). This algorithm is initialised by performing a hierarchical cluster analysis on a small random subset of this dataset comprising 300 of the ~17,000 dryland grid cells. To obtain an initial provisional impression of the effects of initialisation, this first step was performed twice by generating an extra initial random subset (comprised of 300 grid cells) and again performing hierarchical clustering on this new random subset.

Thus, two sets of cluster centres resulted from this randomly repeated hierarchical clustering step, and each of these sets was subsequently used as a random starting point for the *k-means* clustering of the complete dataset. As a consequence of this approach, we generated two cluster partitions of the complete dataset; comparing this pair of partitions provided information regarding the robustness/consistency of the clustering procedure. For this pairwise comparison, the partitions were established by counting the number of grid cells that are allocated to the same cluster in each of this pair and then dividing this number by the total number of grid cells in order to obtain the consistency measure, which is a measure of reproducibility and which illustrates the inherent sensitivity of the *k-means* clustering for initializations.

(2) This pairwise comparison was performed a total of 200 times to obtain a more robust/accurate estimate of this reproducibility measure, thus providing an estimate of the average consistency as well as other key statistics (e.g. variance, quartiles, etc.). Moreover, this repetitive search produced 400 clustering partitions, each from another (random) initialization, and from these 400 partitions the partition with the lowest inner cluster variance was chosen as a candidate optimal partition. Repeated trials of this procedure rendered the same 'optimal' partition for each cluster number *k* considered, thus illustrating the robustness of this partition.

This procedure can also be used to select the 'optimal' number of clusters (the 'optimal' *k*). By performing this repetitive pairwise comparison procedure using various cluster numbers *k* (e.g. $k = 2, \ldots, k_{\max}$) and then calculating the average consistency for each *k*, the *k*-values for which the average consistency is highest will be good candidates for the optimal number of clusters.

Cluster analyses are frequently used to map spatial patterns of specific conditions. In particular, environmental conditions are often grouped using a cluster analysis; for example, to create land cover maps based on satellite data (Kerr & Cihlar, 2003; Yang & Lo, 2002) or to map patterns of climate change (Mahlstein & Knutti, 2010). Cluster analyses can also be used to identify the spatial interactions between humans and their environment, as well as the consequences of these interactions. For example, Ellis and Ramankutty (2008), Letourneau, Verburg, and Stehfest (2012), van Asselen and Verburg (2012), and Václavík, Lautenbach, Kuemmerle, and Seppelt (2013) used cluster analyses to map global distinct land use systems by combining environmental date with socio-economic data. In addition, Sietz, Lüdeke, and Walther (2011) and Kok et al. (2010, accepted) identified global patterns of vulnerability of both drylands and forests to environmental change by accounting for gross domestic product (GDP), infant mortality, road density, water stress, soil degradation, and natural agro-constraints. Nevertheless, to the best of our knowledge, no study has used cluster analysis to spatially describe environmental drivers of human out-migration.

Global hotspots of negative net-migration in drylands

Given the complexity of the migration processes, quantifying the number of migrants at the global level is a major challenge. The Center for International Earth Science Information Network (CIESIN) made such an attempt by mapping migration spatially explicit at the grid cell level over the entire globe (CIESIN, 2011; Sherbinin et al., 2012). Facing the absence of globally accurate migration data at subnational level the authors used indirect estimation methods combining time series of population maps with subnational data regarding birth and death rates to obtain net-migration rates. The resulting net-migration is the grid cell-specific, quantitative difference between in-migration and out-migration. Here, for the purposes of this study, we define negative net-migration as out-migration; the actual out-migration flow might be even higher if in-migration also occurs within the same period. There are a number of uncertainties related to the indirect estimation method, which are largely associated with the assumed relationship between population density and natural increase, the utilized census data, and—most likely causing the biggest uncertainties—the approach to impute rates of natural increase (CIESIN, 2011). The net-migration maps were validated in a way that the sum of net-migration at the national level equals estimates of the 2008 World Population Prospects (United Nations, 2009). In addition, for China and the US CIESIN (2011) compared the simulated net-migration results with net-migration rates from alternative county-level data and concluded a reasonably good correlation between the simulated and alternate net-migration rates. However, evaluating the subnational spatial patterns of net-migration for all countries was not possible, as true measures of net-migration were not available for comparison (CIESIN, 2011).

We used the global map of negative net-migration for the period from 1990 through 2000 (Fig. 2), which we linked to the cluster results to discuss their applicability. Accordingly, we calculated the average negative net-migration per square kilometre for each cluster in order to explore cluster-specific migration patterns. Finally, we selected two hotspots of negative net-migration and discuss the most important environmental and non-environmental constraints (as determined by the published literature) in order to evaluate the identified clusters.

Results

Spatial patterns of environmental incentives for human migration

The presented clusters (see Fig. 3) are a spatial expression of the environmental stressors that potentially cause migration as identified and highlighted by numerous case studies and reports. The cluster algorithm revealed that the optimal cluster number is eight, which provides the most robust results in terms of high average consistency measure. The variability of the indicator values for each cluster is illustrated in Fig. 4.

We identified two desert clusters extending from the Sahara to the Arabian Peninsula and Central Asia. Both of these clusters have high aridity, low precipitation, and the highest drought frequency amongst all clusters. Cropping and grazing are relatively low in both clusters, reflecting the regions' harsh environmental conditions. Nevertheless, soil constraints vary between these clusters. The “Desert with highly constrained soils” cluster has more severe soil constraints than the “Desert with moderately constrained soils” cluster and represents the interior of deserts.

Among all of the eight clusters, the “Little water scarcity” cluster has the least water scarcity. Precipitation is the highest in the “Little water scarcity” cluster, whereas aridity and drought frequency are amongst the lowest. Both cropping and grazing are practiced, with grassland having a larger extent than cropland. The “Little water scarcity” cluster is characterised by land degradation. This cluster primarily occurs at the South of the Sahel towards the more semi-humid regions, Northeast Brazil and along the Argentinian and Paraguayan pampas. The “Grazing under water constraints” cluster is a grazing cluster that is widely distributed but primarily occurs in Central Asia, Eastern Australia, South of Argentina, and the Sahara. Water resources are relatively scarce in this cluster, and this scarcity is reflected by high aridity and low precipitation. Unlike all other clusters that include cropping and grazing activities, land degradation is largely absent in this cluster.

The “Grazing under low soil constraints” cluster is characterised by high levels of grazing activities and low levels of cropping activities. Environmental constraints can be attributed primarily to land characteristics rather than to water availability. This cluster includes vast regions in Central Asia—including Mongolia, China—as well as Australia and Eastern Africa. The “Grazing under medium soil constraints” cluster is similar, except that soil conditions are a more severe constraint. This cluster typically occurs in Central Asia and the United States. The “Moderate soil and water constraints” cluster has medium environmental constraints, with land degradation being a higher environmental stressor than the remaining seven stressors. Together with the relatively poor soils conditions, land degradation is also reflected in the limited availability of cropland. In terms of geographic coverage, this cluster is relatively small, with exemplary locations in the Andes, Botswana, Mexico, Central and Western Australia. The cluster with the best environmental conditions is the “Cropping” cluster, which has the most abundant water and land resources. The cropping cluster includes the largest amount of cropland, even given the high land degradation that occurs in this cluster. This cluster is one of the smallest clusters and occurs primarily in the United States, India, the Mediterranean region, and the border region between Kazakhstan and Russia.

As Fig. 4 shows, the clusters do not necessarily differ from each other in all dimensions but may overlap in some. For example, there is a group of clusters that all show high levels of land degradation, such as the clusters “Little water scarcity”, “Grazing under medium soil constraints”, and “Cropping”, but differ significantly in pasture and crop area. This points at differences, among others, in the quality and management of natural resources.

Linking the patterns of environmental drivers with observed hotspots of negative net-migration

Table 2 shows the mean values for population density, density of negative net-migration and standard deviation (SD), and the share of migrants from the total population for each cluster. Clearly, population density and absolute migrant density vary considerably between the clusters. The absolute numbers of negative net-migration are particularly high in the clusters “Little water scarcity” and “Cropping”, which is not surprising given that these clusters have the highest population density. Moreover, these two clusters—and therefore regions—are easier to access, as they are better connected in terms of transport and infrastructure. These clusters cover wide areas in southern Sahel, the Andes, and Northeast Brazil (“Little water scarcity”), as well as India, East China, and Turkey (“Cropping”). In turn, the two clusters with the lowest population densities (i.e. the two desert clusters) have the lowest absolute numbers of negative net-migration. While the relationship between population density and absolute migration numbers is rather linear across all clusters the relationship between population density and relative numbers of negative net-migrants (i.e. the proportion of negative net-migrants from the entire

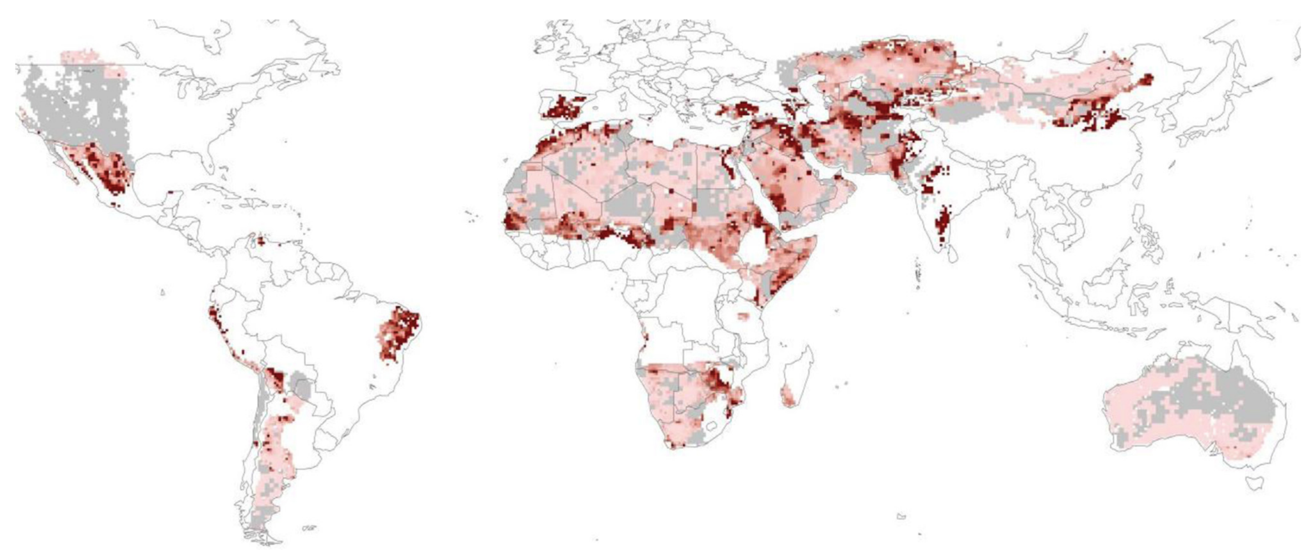

Fig. 2. Dryland regions with negative net-migration from 1990 through 2000. The darker shades of red the more people per square kilometre who out-migrated (ranging from 5 to 240 persons per km^2). Drylands without negative net-migration are depicted in grey. Migration in non-dryland areas is not indicated on this map. Adapted from CIESIN (2011) and Sherbinin (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

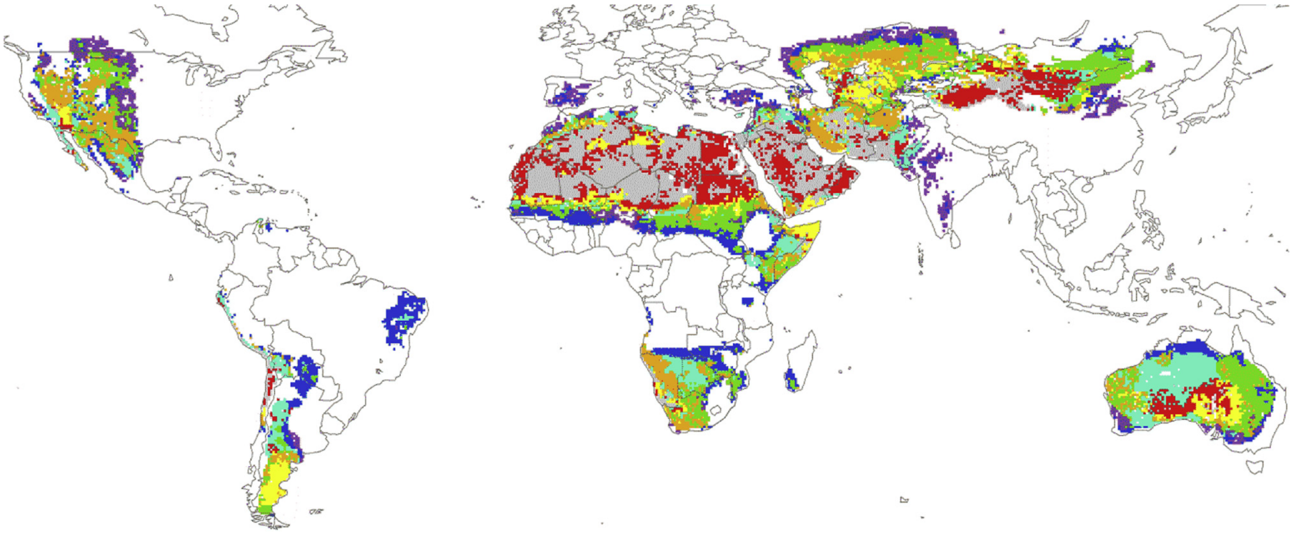

Fig. 3. Spatial distribution of the clusters of environmental drivers of out-migration across global drylands. The colour key to the clusters is provided in Fig. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

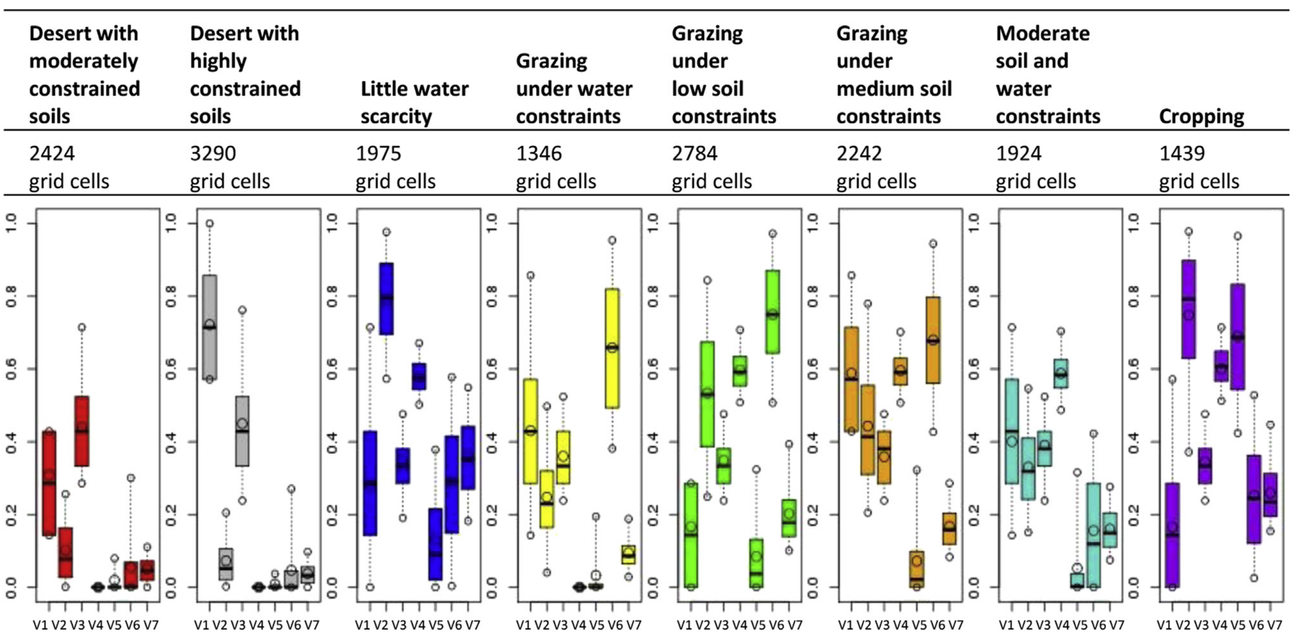

Fig. 4. Variability of indicator values per cluster. The indicators are as follows: V1, soil constraints; V2, aridity; V3, drought frequency; V4, land degradation; V5, crop land; V6, pasture; V7, annual mean precipitation. Note: The boxes present the 25th–75th percentile range of the indicator values (ranging from zero to one); the circles at the end of the dotted lines indicate the 5th and 95th percentiles, and the circle within the box indicates the arithmetic mean; the horizontal bar in the box indicates the median value.

population) per cluster is non-linear (see Fig. 5). For example, the cluster "Cropping"—the cluster with both the highest population density and absolute migration numbers—had the lowest proportion of migrants amongst all of the clusters. In the two sparsely populated desert clusters, high relative negative net-migration was related to various factors. For example, whereas environmental factors contribute primarily to migration in Mauritania, political and economic factors contribute primarily to migration in Somalia. Furthermore, these societies—desert nomads—have typically been characterised by high mobility, given their way of life. Interestingly, the cluster "Little water scarcity" had the second highest absolute migration numbers and one of the highest proportions of migrants amongst all of the clusters, and we can conclude that this cluster is more prone to migration than the other clusters.

Based on Fig. 2, we selected two hotspots of negative net-migration: Burkina Faso and Northeast Brazil. We have chosen these hotspots since 1) they are characterized by high negative net-migration, 2) published literature is available on environmental constraints and how they contribute to outmigration in these regions, and 3) they represent regions with different political, cultural and socio-economic backgrounds which allows us to hint at the global variety of environment-related migration processes in drylands. Here, we describe for both hotspots the most important environmental constraints and discuss whether —and how—these

Table 2
Population and negative net-migration characteristics per cluster.

Cluster	Population density [People per km^2]	Negative net-migration density		Ratio negative net-migrants/total population [%]
		[People per km^2]	[SD]	
Desert with moderately constrained soils	10.88	1.11	5.1	10.16
Desert with highly constrained soils	6.41	0.82	4.1	12.83
Little water scarcity	27.43	3.23	8.6	11.77
Grazing under water constraints	10.81	0.74	1.7	6.81
Grazing under low soil constraints	11.34	1.52	3.6	13.41
Grazing under medium soil constraints	15.61	1.64	3.8	10.50
Moderate soil and water constraints	15.72	1.53	4.3	9.74
Cropping	106.21	6.84	10.7	6.44

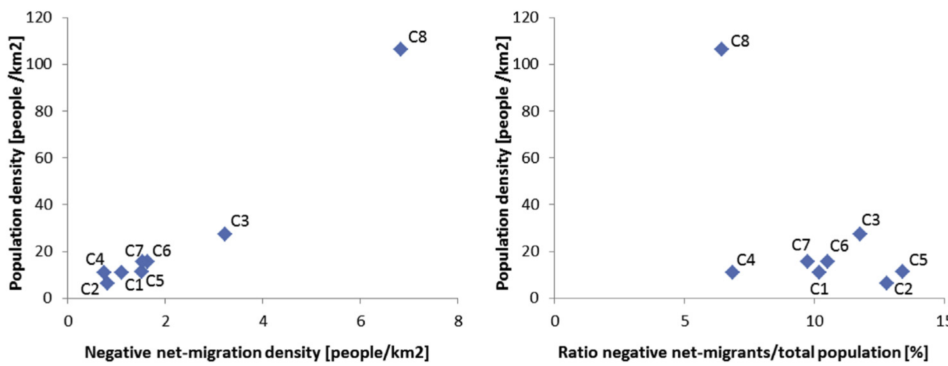

Fig. 5. Relationship between population density and negative net-migration. Left: Population density and absolute negative net-migration per cluster. Right: Population density and fraction of negative net-migration per cluster. The clusters are as follows: C1, Desert with moderately constrained soils; C2, Desert with highly constrained soils; C3, Little water scarcity; C4, Grazing under water constraints; C5, Grazing under low soil constraints; C6, Grazing under medium soil constraints; C7, Moderate soil and water constraints; C8, Cropping.

constraints trigger out-migration. We will use case studies based on published literature to evaluate the identified clusters.

Hotspot 1: Burkina Faso

From 1990 to 2000, the population of Burkina Faso increased rapidly from 9.3 million to 12.3 million and is expected to continue increasing (United Nations, 2010). This population explosion resulted in increased land pressure, which in turn triggered an overexploitation of land resources, for example by reducing fallow periods and increasing the number of livestock. The consequences are the subject of debate; whereas Rochette (1990) argues that pressure on land resources caused land degradation, Gray (1999) emphasises the scale-dependency of land degradation and concludes that land degradation in Burkina Faso can only be confirmed on a large scale but not at the field scale. In our cluster results, the cluster "Little water scarcity"—the highest occurring cluster in Burkina Faso—was characterised by land degradation. As a result of soil degradation, the smallholder and pastoralist systems became more vulnerable to climate variability and other stresses, for example during the droughts in the 1970s. Land pressure—which is expressed in our cluster analysis as the availability of cropland and pasture land— is also reflected in the cluster "Little water scarcity", which contains relatively little pasture land. Although a range of soil and water conservation measures were employed (Maatman, Sawadogo, Schweigman, & Ouedraogo, 1998; Masse et al., 2011), livelihood conditions did not improve sufficiently to prevent migration. In addition, Burkina Faso has a long history of migration, and the Burkinabe are known to be highly mobile both within and across national borders (Cordell, Gregory, & Piché, 1996; Howorth & O'Keefe, 1999). This migration was encouraged by the French colonial government, and after independence, migration was triggered by the rapid expansion of the economy of Côte d'Ivoire and cocoa production (Breusers, 1999). Thus, environmental stressors may trigger migration more strongly in Burkina Faso than in other countries, as migration networks are already in place. In contrast, the political crisis in Côte d'Ivoire, which was partly caused by the high rate of immigration into the country, triggered a massive wave of return migrants to Burkina Faso and caused major problems with the reinsertion of these migrants into an already overburdened land use system (Courtin, 2011). According to our cluster results, compared to regions associated with other clusters, Burkina Faso is restricted relatively little by water availability. The cluster "Little water scarcity" has lower aridity, fewer droughts, and higher precipitation level relatively to the remaining clusters, and land degradation is the primary constraint. In contrast, Henry, Boyle, and Lambin (2003) studied the environment–migration relationship at the national level (rather than at the global level) and found that rainfall variability and land degradation were approximately equally strong determinants of inter-provincial migration in Burkina Faso. On a whole, we can conclude that in Burkina Faso, environmental factors such as land degradation, land pressure, and water availability are potential drivers of out-migration. Nevertheless, the strength at which these drivers operate depends on the scale of the analysis.

Hotspot 2: Northeast Brazil

In Northeast Brazil, smallholders are a major group for whom migration is an important livelihood strategy (Finan & Nelson, 2001; Nelson & Finan, 2009). Because they live in the poorest regions of the country, smallholders in Northeast Brazil are highly constrained with respect to their natural and technological resources (Finan & Nelson, 2001; Sietz et al., 2006). Both agricultural intensification and population growth have increased pressure on the land and triggered land degradation (Lemos, 2001). As a result of land degradation, large areas of Northeast Brazil experienced less profitable agricultural production and a subsequent decrease in on-farm activities in the late 1990s (Sietz et al., 2006). Migration—with regional urban centres and more affluent Southern Brazilian or land reclamation areas in the Amazon region being common migration destinations—is a commonly used strategy to adapt to deteriorated resources (Krol & Bronstert, 2007; Nelson & Finan, 2009). According to our cluster results, Northeast Brazil is part of the cluster "Little water scarcity", which is characterised by land degradation, thereby confirming the findings of the aforementioned local studies. In addition to land degradation, droughts are also an important environmental push factor. In rural Ceará, droughts have historically triggered migration; however, because the government provides food, water, and financial support to drought-affected people, drought-related migration has decreased significantly. Nevertheless, rural-urban migration remains a common livelihood strategy and strategy for coping with droughts (Nelson & Finan, 2009). However, droughts do not occur more frequently in the cluster "Little water scarcity" than in other clusters. From this result, we can conclude either that droughts are insufficiently represented in this cluster or that other environmental factors (such as land degradation and land pressure) are more constraining. Reuveny (2007) estimates that 8 million Brazilians have out-migrated from Northeast Brazil since the 1960s. In addition to droughts, land degradation, water scarcity, and deforestation Reuveny identified population pressure, poverty, unequal land distribution, unclear property rights, and government-subsidised settlers as primary push factors. However, ranking the importance of these factors was beyond the scope of this study. In summary, the evidence suggests that income and employment differences play a key role in explaining migration from Northeast Brazil, and these differences are determined largely by environmental change, including land degradation and drought (Barbieri et al., 2010). This illustrates the role of the environment as an indirect driver of migration and demonstrates how tightly environmental and economic factors can be intertwined, thus making it nearly impossible to attribute migration to one or both factors.

Discussion

Results

Spatially, the environmental drivers of migration vary widely. To identify large-scale regions containing similar environmental drivers, we performed a cluster analysis using spatially explicit data. This analysis allowed us to identify the most pressing environmental conditions (per grid cell and region) that potentially contribute to out-migration. In doing so, we could distinguish regions that are characterised primarily by land-related drivers of out-migration from regions that are characterised primarily by water-related drivers of migration. For example, the two clusters that had the highest population densities and the largest crop land extent (namely, the "Little water scarcity" and "Cropping" clusters) had high land degradation and the lowest water scarcity among all eight clusters. We therefore argue that within these two clusters, land degradation is a stronger determinant of out-migration than water. Given their high population density and cropping activities, these clusters are particularly vulnerable to increasing land degradation and food insecurity. In contrast, water scarcity (expressed in terms of aridity, precipitation, and drought frequency) is the highest in the desert clusters ("Desert with moderately constrained soils" and "Desert with highly constrained soils"). Viewing these two clusters in the context of potential absolute migration flows may not be particularly relevant, given the low population density and nomadic culture typical of desert regions. On the other hand, the interaction of socio-political and environmental factors in migration processes in these two clusters is significant. For example, in Northern Mali the advance of extremist Muslim groups and Al-Qaida recently triggered migration of people both internally in Mali and to neighbouring countries. Particularly in Mali, the displaced civilians are distributed across arid areas contributing to food insecurity and tensions among the various communities, which potentially triggers new migration flows (UNHCR, 2014). This example emphasises the important role that socio-political factors—through their interplay with environmental factors—play in influencing migration. Given the relatively high frequency of political upheaval in drylands (particularly in Africa), there might be a correlation between fragile environmental conditions, the specific demographic profile and the relatively low level of government involvement in these areas that results from these environmental and demographic conditions.

We found that in particular regions, a specific combination of environmental factors goes hand-in-hand with a high rate of negative net-migration. For example, our results suggest that both high absolute and high relative rates of negative net-migration occur most often in the "Little water scarcity" cluster that covers the southern regions of the Sahel, the more semi-arid regions of Southern Africa, Northeast Brazil, and the Argentinian and Paraguayan pampas. This cluster is therefore more prone to out-migration than other clusters. However, identifying the extent to which the observed negative net-migration can be related directly to cluster-specific environmental constraints is difficult, as the applied migration data do not specify the reasons for migration. Other factors (including non-environmental factors) that were not considered in our analysis have likely triggered migration as well. Our findings are further supported by the results of the hotspot analyses, which illustrate the complexity of environmental and non-environmental factors in migration processes. Given the combination of high negative net-migration rates together with the identified environmental constraints, we argue that the most pressing environmental factors driving this cluster—including land degradation—have contributed to the observed out-migration in the respective regions.

Environmental versus non-environmental drivers of migration

Adverse environmental conditions can be either partially or completely offset by strong socio-economic and governance conditions, which inevitably raises the question of the importance of environmental factors alone when explaining the human-environment system. For example, Henry et al. (2003) show that migration in Burkina Faso can empirically be better explained using a combination of environmental and socio-economic factors rather than environmental factors alone. With respect to our clusters, the effect of high aridity as for example identified for the cluster "Grazing under water constraints" may be limited by the use of efficient irrigation facilities. However, in addition to the requirement for available water resources, farmers must also possess the knowledge and skills needed for the efficient use of irrigation water, and they must have the necessary funds to invest in an appropriate irrigation infrastructure. Another factor that can offset the effects of adverse environmental conditions on migration is the presence of alternative employment opportunities and income, for example from oil industries in North Africa and the Middle East, which may explain the relative paucity of out-migration in these regions. With respect to economic and governance conditions, considerable differences exist between regions and countries, which may improve adverse environmental conditions in some regions whilst making them worse in others. Although this integration of environmental, political, and socio-economic factors is essential for realistic future assessments of potential migration in drylands, such an assessment was beyond the scope of our study, as our goal was to provide a better representation of the environmental drivers of migration. Moreover, reliable and spatially explicit data regarding the socio-economic drivers of migration are rare, thereby hampering our ability to obtain a complete picture.

Policy implications

The results presented in this paper suggest cluster-specific policies to remedy observed migration patterns. Here, we illustrate possible entry points for strategic interventions for a few exemplary clusters. In the four most water limited clusters, namely the two desert clusters, the “Grazing under water constraints” cluster, and the “Moderate soil and water constraints” cluster major interventions would be required to better deal with the pronounced water scarcity including measures to store and use existing water resources more efficiently and decrease water withdrawal. In many developing countries where high aridity, high drought frequency and low precipitation combines with limited institutional capacities in the water sector (ECA, 2000), low cost water-saving strategies for livestock keeping and cropping should be fostered rather than increasing water availability per se. Moreover, organising water rights can provide farmers and herders with added certainty regarding water access, and this may help reduce vulnerability due to water stress. In addition, the “Grazing under water constraints” cluster would additionally benefit from readjustments of grazing intensities. This may necessitate strategies for developing alternative land-independent livelihoods. In the “Little water scarcity” cluster— which has shown to be particularly prone to out-migration—interventions would particularly target land rehabilitation and improvement in land access. For example, in the rural areas of Northeast Brazil (falling into this cluster), where the majority of farmers face difficulties to make a living due to severe land degradation and poverty, interventions would focus on improving soil quality and vegetation cover based on conservation measures (Sietz, 2014). Better access to fertile land, which is largely concentrated in the hands of large-holder farmers, would further contribute to mediate the causes for out-migration due to expected positive effects on agricultural production. Given the global coverage of our study, these policy implications are necessarily broad implying the need for regional adjustments to adequately reflect specific underlying processes, social groups and implementation approaches (Birkmann, 2007). In addition, policies for better managing migration need to be integrated into the wider development strategies to be successful. This integration does not only require appropriate knowledge and resources, but furthermore strongly relies on supporting institutions, which are however frequently lacking in the climate adaptation domain (Biesbroek, Klostermann, Termeer, & Kabat, 2013). Therefore, refined policies for migration management need to be operationalised while considering the specific institutional context in the regions targeted.

Summary and conclusions

Migration is a widely recognised consequence of environmental change and, environment-induced migration has been given priority on international policy agendas. For example, migration has been formally introduced into the regime of the United Nations Framework Convention on Climate Change (UNFCCC) with the agreement on the Cancun Adaptation Framework at the 2010 UNFCCC COP16 meeting, which invited all interested parties to partake in ‘measures to enhance understanding, co-ordination and co-operation with regard to climate-change induced displacement, migration and planned relocation, where appropriate’ (UNFCCC, 2010). However, despite its clear relevance, research regarding the potential for human systems—including migration—to adapt to environmental change is less advanced than research regarding biophysical systems, ecological impacts, and the mitigation of environmental change (Wilbanks et al., 2007). Our study represents an empirical contribution to the description of environmental drivers of migration at the macro-scale. Our goal was to explore potential environmental drivers of human migration using a spatially explicit analysis and link those drivers to observed hotspots of out-migration. To achieve this goal, we performed a cluster analysis. Using the applied methodology, we identified the most severe environmental constraints in each cluster (and therefore, in each region). We show that the clusters—and the most severe environmental constraints and potential migration incentives—can vary widely across space. We therefore conclude that in addition to regional strategies, location-specific measures are needed to adequately address environmentally motivated migration. On the other hand, the results do not support ranking the regions based on their environmental characteristics along a gradient from low migration incentives to high migration incentives. Therefore, a spatially explicit ranking of regions based on the impact of their environmental drivers of migration is currently out of reach.

We can draw several conclusions from our hotspot analysis. First, environmental factors play a major role in migration processes in Burkina Faso and Northeast Brazil. In these two regions, adverse environmental conditions likely cause a decline in the livelihood of the rural population, who usually respond with out-migration. Second, alternative income opportunities in other rural areas (Burkina Faso) or urban areas (Burkina Faso and Brazil) act as strong pull factors in combination with environmental degradation acting as a push factor. This combination of pull and push factors demonstrates the strong interdependence between environmental and economic factors, and it underscores the challenge in identifying the root cause of migration. Third, the scale of analysis likely influences the findings. The results of the global scale cluster analysis suggest that land degradation is the most severe environmental constraint for both hotspots. However, national-level analyses for Burkina Faso revealed that rainfall variability and soil degradation are approximately equally strong determinants of intra-provincial migration. With respect to Brazil, we conclude that similar differences likely exist between outcomes from the global and national scales. These findings suggest that one must select the scale of the analysis carefully based on the context of the study and the available data.

The approach presented here is particularly valuable for describing environmental factors that influence migration in drylands using a spatially explicit method. However, identifying the trigger points for out-migration and quantifying actual stocks or flows of environmentally motivated migrants will require a more in-depth understanding of the underlying mechanisms in which socio-economic and political factors interact with environmental drivers of human migration. Consequently, the clusters identified here can be used to discuss possible migration incentives—especially incentives related to environmental pressures—rather than to explain the migration dynamics themselves.

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References

Adger, W. N., Pulhin, J. M., Barnett, J., Dabelko, G. D., Hovelsrud, G. K., Levy, M., Oswald Spring, Ú., & Vogel, C. H. (2014). Human security. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 755–791). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

van Asselen, S., & Verburg, P. H. (2012). A Land System representation for global assessments and land-use modeling. *Global Change Biology, 18*(10), 3125–3148.

Bai, Z. G., Conijn, J. G., Bindraban, P. S., & Rutgers, B. (2012). Global changes of remotely sensed greenness and simulated biomass production since 1981: Towards mapping global soil degradation. In *ISRIC report* (Vol. 2012/02). Wageningen.

Barbieri, A., Domingues, E., Queiroz, B., Ruiz, R., Rigotti, J., Carvalho, J., et al. (2010). Climate change and population migration in Brazil's Northeast: scenarios for 2025–2050. *Population & Environment, 31*(5), 344–370.

Biesbroek, G. R., Klostermann, J. M., Termeer, C. A. M., & Kabat, P. (2013). On the nature of barriers to climate change adaptation. *Regional Environmental Change, 13*(5), 1119–1129.

Birkmann, J. (2007). Risk and vulnerability indicators at different scales: applicability, usefulness and policy implications. *Environmental Hazards, 7*(1), 20–31.

Black, R., Adger, W. N., Arnell, N. W., Dercon, S., Geddes, A., & Thomas, D. (2011). The effect of environmental change on human migration. *Global Environmental Change, 21S*, S3–S11.

Bowyer, C., Withana, S., Fenn, I., Bassi, S., Lewis, M., Cooper, T., et al. (2009). *Land degradation and desertification*. European Parliament, Policy Department Economic and Scientific Policy.

Breusers, M. (1999). *On the move: Mobility, land use and livelihood practices on the Central Plateau in Burkina Faso*. Hamburg: Literatur Verlag.

Brockhaus, M., Djoudi, H., & Locatelli, B. (2013). Envisioning the future and learning from the past: adapting to a changing environment in northern Mali. *Environmental Science & Policy, 25*(0), 94–106.

CIESIN. (2011). Migration and global environmental change. In *MR4: Estimating net migration by ecosystem and by decade: 1970–2010* (p. 129). Center for International Earth Science Information Network (CIESIN), The Earth Institute at Columbia University.

Conijn, J., Bai, Z., Bindraban, P., & Rutgers, B. (2013). *Global changes of net primary productivity, affected by climate and abrupt land use changes since 1981. Towards mapping global soil degradation*. Report 2013/01. Wageningen: ISRIC—World Soil Information. ISRIC Report, 1.

Cordell, D. D., Gregory, J. W., & Piché, V. (1996). *Hoe and wage: A social history of a circular migration system in West Africa*. Westview Press Boulder, CO.

Courtin, F. (2011). La crise ivoirienne et les migrants burkinabés. *Afrique Contemporaine, 4*, 11–27.

De Haas, H. (2010). Migration transitions: a theoretical and empirical inquiry into the developmental drivers of international migration. In *International migration institute working papers* (Vol. 24)International Migration Institute, University of Oxford.

ECA. (2000). *The africa water vision for 2025: Equitable and sustainable use of water for socioeconomic development*. Addis Ababa, Ethiopia: Economic Commission for Africa, African Union and African Development Bank.

Ellis, E. C., & Ramankutty, N. (2008). Putting people in the map: anthropogenic biomes of the world. *Frontiers in Ecology and the Environment, 6*(8), 439–447.

Finan, T. J., & Nelson, D. R. (2001). Making rain, making roads, making do: public and private adaptations to drought in Ceará, Northeast Brazil. *Climate Research, 19*(2), 97–108.

Foresight. (2011). *Migration and global environmental change: Future challenges and opportunities*. London: The Government Office for Science.

van der Geest, K., & Dietz, T. (2004). A literature survey about risk and vulnerability in drylands, with a focus on the sahel. In *The impact of climate change on drylands* (Vol. 39, pp. 117–146).

Gemenne, F. (2011). Why the numbers don't add up: a review of estimates and predictions of people displaced by environmental changes. *Global Environmental Change, 21S*, S41–S49.

Gray, L. C. (1999). Is land being degraded? A multi-scale investigation of landscape change in southwestern Burkina Faso. *Land Degradation & Development, 10*(4), 329–343.

Gray, C., & Müller, V. (2012). Drought and population mobility in rural Ethiopia. *World Development, 40*(1), 134–145.

Grote, U., & Warner, K. (2010). Environmental change and migration in Sub-Saharan Africa. *International Journal of Global Warming, 2*(1), 17–47.

Henry, S., Boyle, P., & Lambin, E. F. (2003). Modelling inter-provincial migration in Burkina Faso, West Africa: the role of socio-demographic and environmental factors. *Applied Geography, 23*(2–3), 115–136.

Henry, S., Schoumaker, B., & Beauchemin, C. (2004). The impact of rainfall on the first out-migration: a multi-level event-history analysis in Burkina Faso. *Population and Environment, 25*(5), 423.

Howorth, C., & O'Keefe, P. (1999). Farmers do it better: local management of change in southern Burkina Faso. *Land Degradation & Development, 10*(2), 93–109.

IIASA/FAO. (2012). *Global Agro-ecological Zones (GAEZ v3.0)*. Laxenburg, Austria/Rome, Italy: IIASA/FAO.

IIED. (2008). *Climate change and drylands*. International Institute for Environmental Development.

IOM. (2008a). Migration and climate change. In *IOM migration research studies* (Vol. 31).

IOM. (2008b). Migration, development and environment. In *IOM migration research studies* (Vol. 35).

Janssen, P., Walther, C., & Lüdeke, M. (2012). Cluster analysis to understand socio-ecological systems: A guideline. In *PIK report* (Vol. 126, p. 96). Potsdam: Potsdam Institute for Climate Impact Research.

Kerr, T., & Cihlar, J. (2003). Land use and cover with intensity of agriculture for Canada from satellite and census data. *Global Ecology & Biogeography, 12*, 161–172.

Kok, M., Lüdeke, M., Lucas, P., Sterzel, T., Walther, C., Janssen, P., Sietz, D., de Soysa, I. A new method for analysing patterns of vulnerability, Accepted in Regional Environmental Change.

Kok, M. T. J., Lüdeke, M. K. B., Sterzel, T., Lucas, P. L., Walter, C., Janssen, P., et al. (2010). Quantitative analysis of patterns of vulnerability to global environmental change. In *PBL background studies*. Den Haag/Bilthoven: Netherlands Environmental Assessment Agency (PBL).

Krol, M. S., & Bronstert, A. (2007). Regional integrated modelling of climate change impacts on natural resources and resource usage in semi-arid Northeast Brazil. *Environmental Modelling & Software, 22*(2), 259–268.

Lee, E. S. (1966). A theory of migration. *Demography, 3*(1), 47–57.

Lemos, J. J. S. (2001). Niveis de degradacão no Nordeste Brasileiro. *Revista Econômica do Nordeste, 32*, 406–429.

Letourneau, A., Verburg, P. H., & Stehfest, E. (2012). A land-use systems approach to represent land-use dynamics at continental and global scales. *Environmental Modelling & Software, 33*(0), 61–79.

Maatman, A., Sawadogo, H., Schweigman, C., & Ouedraogo, A. (1998). Application of zai and rock bunds in the northwest region of Burkina Faso: study of its impact on household level by using a stochastic linear programming model. *NJAS Wageningen Journal of Life Sciences, 46*(1), 123–136.

Mahlstein, I., & Knutti, R. (2010). Regional climate change patterns identified by cluster analysis. *Climate Dynamics, 35*(4), 587–600.

Marchiori, L., Maystadt, J.-F., & Schumacher, I. (2012). The impact of weather anomalies on migration in sub-Saharan Africa. *Journal of Environmental Economics and Management, 63*(3), 355–374.

Masse, D., Hien, E., Kaboré, T., Bilgo, A., Hien, V., & Chotte, J.-L. (2011). Evolution of farming practices in sub-Saharan region confronted by demographic and climatic changes: runoff control and organic matter resources management. *Procedia Environmental Sciences, 9*(0), 124–129.

McLeman, R., & Hunter, L. M. (2010). Migration in the context of vulnerability and adaptation to climate change: insights from analogues. *Wiley Interdisciplinary Reviews: Climate Change, 1*(3), 450–461.

McLeman, R., & Smit, B. (2006). Migration as an adaptation to climate change. *Climatic Change, 76*(1), 31–53.

Mehta, L. (2007). Whose scarcity? Whose property? The case of water in western India. *Land Use Policy, 24*(4), 654–663.

Meze-Hausken, E. (2000). Migration caused by climate change: how vulnerable are people inn dryland areas? *Mitigation and Adaptation Strategies for Global Change, 5*(4), 379–406.

Mitchell, T. D., & Jones, P. D. (2005). An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology, 25*(6), 693–712.

Nelson, D. R., & Finan, T. J. (2009). Praying for drought: persistent vulnerability and the politics of patronage in Ceará, Northeast Brazil. *American Anthropologist, 111*(3), 302–316.

Perch-Nielsen, S., Bättig, M., & Imboden, D. (2008). Exploring the link between climate change and migration. *Climatic Change, 91*(3–4), 375–393.

Piguet, E. (2012). From "primitive migration" to "climate refugees": the curious fate of the natural environment in migration studies. *Annals of the Association of American Geographers, 103*(1), 148–162.

Piguet, E., Pécoud, A., & de Guchteneire, P. (2011). Migration and climate change: an overview. *Refugee Survey Quarterly, 30*(3), 1–23.

Ramankutty, N., Evan, A. T., Monfreda, C., & Foley, J. A. (2008). Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles, 22*.

Reuveny, R. (2007). Climate change-induced migration and violent conflict. *Political Geography, 26*(6), 656–673.

Richmond, A. (1995). The environment and refugees: theoretical and policy issues. *Population Bulletin of the United Nations, 39*, 1–17 (0251–7604 (Print)).

Rochette, R. (1990). *Le Sahel en lutte contre la de'sertification: leçons d'expe'rience*. Ouagadougou,Burkina: CILSS/GTZ.

Roncoli, C., Ingram, K., & Kirshen, P. (2001). The costs and risks of coping with drought: livelihood impacts and farmers' responses in Burkina Faso. *Climate Research, 19*(2), 119–132.

Safriel, U., & Adeel, Z. (2005). Dryland systems. In *Millennium ecosystem assessment*. Washington, DC: Island Press.

Scheffran, J., Marmer, E., & Sow, P. (2012). Migration as a contribution to resilience and innovation in climate adaptation: social networks and co-development in Northwest Africa. *Applied Geography, 33*(0), 119–127.

Sherbinin, A. D., Levy, M., Adamo, S., MacManus, K., Yetman, G., Mara, V., et al. (2012). Migration and risk: net migration in marginal ecosystems and hazardous areas. *Environmental Research Letters, 7*(4), 045602.

Siebert, S., Döll, P., Hoogeveen, J., Faures, J. M., Frenken, K., & Feick, S. (2005). Development and validation of the global map of irrigation areas. *Hydrology and Earth System Sciences, 9*(5), 535–547.

Siebert, S., Hoogeveen, J., & Frenken, K. (2006). Irrigation in Africa, Europe and Latin America. Update of the digital global map of irrigation areas to version 4. In *Frankfurt hydrology paper* (Vol. 5, p. 134). Frankfurt am Main, Germany: U. o. F. Institute of Physical Geography.

Sietz, D. (2014). Regionalisation of global insights into dryland vulnerability: better reflecting smallholders' vulnerability in Northeast Brazil. *Global Environmental Change, 25*, 173–185.

Sietz, D., Lüdeke, M. K. B., & Walther, C. (2011). Categorisation of typical vulnerability patterns in global drylands. *Global Environmental Change, 21*(2), 431–440.

Sietz, D., Untied, B., Walkenhorst, O., Lüdeke, M. K. B., Mertins, G., Petschel-Held, G., et al. (2006). Smallholder agriculture in Northeast Brazil: assessing heterogeneous human-environmental dynamics. *Regional Environmental Change, 6*(3), 132–146.

Sissoko, K., Keulen, H., Verhagen, J., Tekken, V., & Battaglini, A. (2011). Agriculture, livelihoods and climate change in the West African Sahel. *Regional Environmental Change, 11*(1), 119–125.

Suhrke, A. (1993). Pressure points: environmental degradation, migration and conflict. In *Environmental change, population displacement, and acute conflict, Ottawa, Canada*.

Trabucco, A., & Zomer, R. J. (2009). *Global aridity index (global-aridity) and Global Potential Evapo-Transpiration (Global-PET) geospatial database*. Published online available from the CGIAR-CSI GeoPortal at. CGIAR Consortium for Spatial Information http://www.csi.cgiar.org.

Tucker, C. J., Pinzon, J. E., & Brown, M. E. (2004). *Global Inventory Modeling and Mapping Studies (GIMMS) satellite drift corrected and NOAA-16 incorporated normalised difference vegetation index (NDVI), monthly1981–2002*. University of Maryland.

UNCCD. (2013). *UNCCD factsheets*. http://www.unccd.int/en/resources/Library/Pages/Fact.aspx Accessed 01.11.14.

UNFCCC. (2010). *Outcome of the work of the Ad Hoc Working Group on long-term Cooperative Action under the Convention, CP 16*. http://unfccc.int/files/meetings/cop_16/application/pdf/cop16_lca.pdf#page=3,para14(f) Accessed 01.11.14.

UNHCR. (2014). *2014 UNHCR country operations profile – Mali*. http://www.unhcr.org/pages/49e484e66.html Accessed 01.11.14.

United Nations, Population Division. (2009). *World population prospects: The 2008 revision*. New York: United Nations, Department of Economic and Social Affairs, Population Division.

United Nations, Population Division. (2010). *World population prospects, the 2010 revision*. New York: United Nations, Department of Economic and Social Affairs, Population Division.

Václavík, T., Lautenbach, S., Kuemmerle, T., & Seppelt, R. (2013). Mapping global land system archetypes. *Global Environmental Change, 23*(6), 1637–1647.

Van der Geest, K., Vrieling, A., & Dietz, T. (2010). Migration and environment in Ghana: a cross-district analysis of human mobility and vegetation dynamics. *Environment and Urbanization, 22*(1), 107–123.

Wilbanks, T. J., Romero Lankao, P., Bao, M., Berkhout, F., Cairncross, S., Ceron, J.-P., Kapshe, M., Muir-Wood, R., & Zapata-Marti, R. (2007). Industry, settlement and society. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (Eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 357–390). Cambridge, UK: Cambridge University Press.

Yang, X., & Lo, C. P. (2002). Using a time series of satellite imagery to detect land use and land cover changes in the Atlanta, Georgia metropolitan area. *International Journal of Remote Sensing, 23*(9), 1775–1798.