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# Emerging migration flows in a changing climate in dryland Africa

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**Fears of the movement of large numbers of people as a result of changes in the environment were first voiced in the 1980s (ref. 1). Nearly thirty years later the numbers likely to migrate as a result of the impacts of climate change are still, at best, guesswork[2]. Owing to the high prevalence of rainfed agriculture, many livelihoods in sub-Saharan African drylands are particularly vulnerable to changes in climate. One commonly adopted response strategy used by populations to deal with the resulting livelihood stress is migration. Here, we use an agent-based model developed around the theory of planned behaviour to explore how climate and demographic change, defined by the ENSEMBLES project[3] and the United Nations Statistics Division of the Department of Economic and Social Affairs[4], combine to influence migration within and from Burkina Faso. The emergent migration patterns modelled support framing the nexus of climate change and migration as a complex adaptive system[5]. Using this conceptual framework, we show that the extent of climate-change-related migration is likely to be highly nonlinear and the extent of this nonlinearity is dependent on population growth; therefore supporting migration policy interventions based on both demographic and climate change adaptation.**

As part of the United Nations Framework Convention on Climate Change, the Cancun Adaptation Framework urges all parties to develop measures to enhance understanding, coordination and cooperation with regard to climate-change-induced displacement, migration and planned relocation (http://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf#page=4paragraph14(f)). Although this statement mirrors the concerns of policymakers regarding the social implications of climate change, there is growing consensus that climate change cannot, in most cases, be isolated from other macrolevel economic, political, social and demographic drivers of migration[6–9]. Furthermore, it is also recognized that migration behaviour is determined by a host of microlevel factors including access to the variety of capitals needed to migrate, the viability of alternative livelihood strategies, the extent of institutional barriers to migration[10] and, as a socially mediated process[11], the behaviour of others through the formation of attitudes towards migration and access to migration networks. For example, in Burkina Faso as elsewhere, economic factors, including income differentials and shocks, are often cited as the key variables explaining migration by households confronted with severe scarcity of natural resources[12].

Characterized by low rainfall, high evaporation and subsequently limited soil moisture and biomass production, drylands occupy more than 40% of the Earth's land surface and are occupied by approximately one-third of the world's population at present[13]. One of the poorest countries in the world, the population and economy of the dryland country of Burkina Faso largely depend on rainfed agriculture and cattle raising, making many communities throughout the country sensitive to changes in climate. This sensitivity, coupled with the historically mobile population of Burkina Faso[14], makes the country an appropriate case study for an investigation into the issue of migration influenced by climate change in dryland Africa.

The behaviour of groups of individuals and households can be quantified in a number of ways. One approach is the use of agent-based models (ABMs) applied within the framework of a complex adaptive system whereby autonomous and heterogeneous entities, whose individual circumstances and behaviour are different to an average meta-actor, experience multidimensional interactions with each other and their environment across varying spatial, temporal and social scales[3,15]. Climate conditions can, for example, influence individual economic behaviour both locally through stress on agricultural production and globally through impacts on seed and produce prices. Although ABMs have been used previously in a number of other environmental contexts, little attention has been focused on their use in migration studies. In the few cases where migration has been modelled using ABMs, these have taken the form of simulations based around differences of earnings between source and destination regions within which the individual is assumed to be a rational actor[16–18]. Such applications, however, neglected to include the explicit influence of an individual's perception of migration opportunities and constraints and the role of other peoples' behaviour on the migration decision-making process.

Migration as a response to the impacts of climate change exists along an adaptation[19] continuum ranging from the reactive behaviour of displacement to the planned response of seasonal migration to diversify and maintain household income in the face of increased stress on livelihoods. Here, we focus on migration that tends towards the adaptive end of the climate-related migration spectrum, with individuals migrating seasonally. In this context we are able to call on the theory of planned behaviour[20] to conceptually drive the development of the ABM. The theory of planned behaviour consists of the sociocognitive variables of attitudes towards behaviour, subjective norms and perceived behavioural control.

In the ABM presented here, Burkina Faso is divided into five zones: the northern Sahel region; the centre; the southwest; and the two primary urban centres of Ouagadougou and Bobo-Dioulasso. Migration is defined as relocation by an agent from one model zone to another or out of the country (international) and is restricted to annual seasonal migration for the duration of the dry season (October to May). Agents are defined in the model as individuals classified according to attributes of age, gender, marital status and geographic location. An agent's attitude towards migration behaviour is represented as the probability of migration from one model zone to another, based on their personal attributes and according to the rainfall variability they have experienced in the previous three years. This formulation of the agent's behavioural attitude follows a multivariate analysis of data from the Enquête Migration, Insertion Urbaine et Environnement au Burkina Faso

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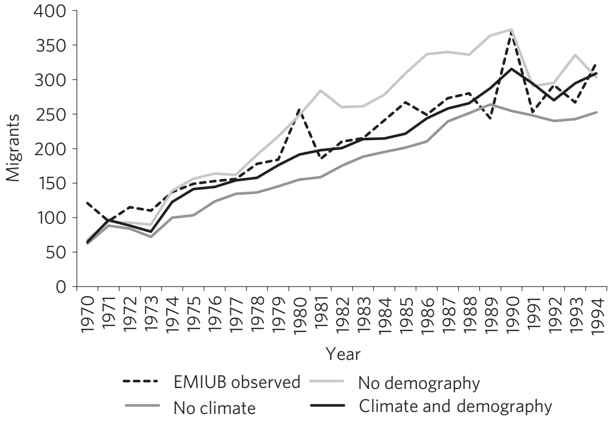


**Figure 1 | ABM simulated and EMIUB observed migration flows in and from Burkina Faso for the period 1970–1994.** Simulations start with populations of 4,449 agents. Model runs (and statistical comparisons with the observed data) are shown with rainfall variability using a light grey line ($r = 0.91$, RMSE = 15.96%); only demography using a dark grey line ($r = 0.92$, RMSE = 24.04%); and both rainfall variability and demography using a black line ($r = 0.94$, RMSE = 11.65%); where $r$ is the correlation coefficient and RMSE is the root mean squared error. Observed data is shown with a dashed line. Owing to the probabilistic nature of the ABM, all results in this and subsequent figures are the average of four (ensemble) runs of the model.

(EMIUB; ref. 21) retrospective multilevel family-type survey and focus group findings from interviews conducted by the authors in Burkina Faso. Multivariate analysis using the EMIUB data (included as Supplementary Information) reveals the statistical significance (at <0.01 level) of age, gender, marital status and zone of origin variables in determining migration outcomes. Although the overall significance of rainfall variability is shown at only the 0.26 level, this was expected from a previous analysis of the data[22] that reported a statistically significant relationship between rainfall variability and migration only when differentiated in terms of the destination of the migrants.

Individual-level data from the EMIUB from 1990 to 1999 was used to parameterize the model. Although it is recognized that migratory decisions are often made at the household level[23], the agents used in the ABM are not arranged into households, to avoid the added complexity of household-level interactions in this version of the model. Differentiating between agents in terms of their personal attributes allows their position in the household to be implicitly incorporated into the model and the influence of wider social networks to be considered. In this conception of migration the driving variable of rainfall can be considered as a proxy for the many ways in which climate influences individual livelihood choices in a rainfed agricultural economy. For this reason, income differentials and shocks are not included in the model.

The influence of other agents on the behaviour of an individual agent in the ABM is defined through a small-world representation of social networks[24] and parameterized using the EMIUB data. The key variable in this parameterization is the proportion of networked peers that have also migrated, used to define a function (see Supplementary Information) through which the behavioural attitude probability is adjusted. Migration flows shown are thus the total migration flux, defined as movement from one model zone to another, and are an aggregate of internal and international migration.

In Fig. 1 the observed flow of migrants in and from Burkina Faso, as recorded by the EMIUB retrospective multilevel migration history survey of 4,449 individuals, is shown alongside modelled migration flows from an ABM for the period 1970–1994. The modelled data shown in this figure are derived using real agents with initial 1970 characteristics matching those of the individuals surveyed in Burkina Faso in 2000. These results illustrate the ability of the model to replicate the trend in migration in Burkina Faso as well some of the year-to-year variability; although it is recognized that improvements in the performance of the model would be possible if data were used that were collected for the purpose of the ABM development. The 25-year period of comparison was selected to reduce the influence of the premature death of agents in the model that are not included in the retrospective life histories. Information on climate change for the region was obtained from the ENSEMBLES project[3], which provides monthly rainfall data from eight regional climate models at a spatial resolution of 50 km by 50 km. The rainfall trends resulting from each scenario, determined in terms of the classification of each year as having above-average, normal or below-average rainfall, are shown in Table 1 for the three non-urban model zones of Burkina Faso. The disparity between rainfall scenarios demonstrates the present level of uncertainty between different models of future rainfall in dryland West Africa to 2050.

Figure 2 shows simulated migration flows from ensemble runs of the ABM for a range of demographic[4] and climate scenarios. Migration rates are shown as the difference between the numbers of migrants modelled using the different rainfall scenarios and those modelled under a scenario that repeats the 1970–1999 rainfall, normalized by the size of the original population of agents. In particular, the dry and wet scenarios of SMHIRCA and KNMI-RACMO2, respectively, are indicated by the marked curves. These show that, when considering a climate scenario that tends towards increased wetter conditions (KNMI-RACMO2), migration falls relative to that that would be expected with present climate conditions. However, a change in the climate towards drier conditions (SMHIRCA), shows only limited periods of slightly higher migration relative to that that would be produced under present climate conditions. These patterns of change are more evident under higher degrees of demographic change.

**Table 1 | Rainfall classification scenarios resulting from each of the ENSEMBLES rainfall data sets in Sahel, centre and southwest zones of Burkina Faso.**

| Rainfall Data set | Sahel | Centre | Southwest |
|---|---|---|---|
| MPI-M-REMO (mp) | Average-dry | Average | Average-wet |
| METO-HC HadRM3 (had) | Wet | Wet | Average |
| KNMI-RACMO2$^{(Wet)}$ (kn) | Wet | Wet | Wet |
| SMHIRCA$^{(Dry)}$(sm) | Dry | Dry | Dry |
| GKSS-CCLM4.8 (gk) | Average-wet | Average-wet | Average-dry |
| ICTP-REGCM3 (ic) | Average-dry | Average-wet | Average-wet |
| DMI-HIRHAM5 (dm) | Average-dry | Average | Average-wet |
| METNOHIRHAM (met) | Average-dry | Average-dry | Dry |

Dry and wet notations indicate rainfall data sets that result in the most consistently dry and wet scenarios, respectively.

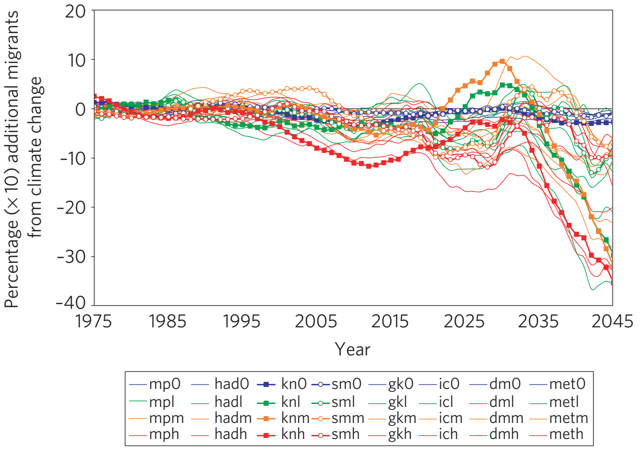


**Figure 2 | Simulated differences in the percentage of the original population migrating under different climate conditions and that assuming the past climate.** Four demographic scenarios are considered as depicted by: 0, referring to no population growth; l, referring to a low-population-growth scenario; m, referring to a medium-population-growth scenario; and h, referring to a high-population-growth scenario, as defined by the United Nations, Department of Economic and Social Affairs, Population Division. Different model types are indicated by their acronyms in Table 1 and differences are ten-year averages. Differences in migration assuming dry and wet scenarios of SMHIRCA and KNMI-RACMO2, respectively, are indicated by the curves with open circle and closed square markers.

In Fig. 3 the annual migration fluxes, as a percentage of the original population for the different climate scenarios, are shown against the migration flux as a percentage of the original population without climate change for all demographic scenarios. These results show that, with both the progression of time and an increase in the percentage of the original population migrating (owing to population growth), the envelope of migration possibilities diverges from that that would be expected without climate change. This divergent behaviour is again shown as occurring only when population growth is included in the ABM.

The envelope of migration futures under climate change is clearly influenced by most of the ENSEMBLES scenarios depicting a wetting rainfall trend, although the drier scenarios (for example, SMHIRCA) do depict periods of enhanced migration, particularly when separated by destination (see Supplementary Information). This emergent behaviour is thought to reflect the feedback of agents communicating migratory behaviour to other agents in their social network. Such messages play a part in altering an individual agent's likelihood of migrating; an outcome that may then have an impact on the migratory behaviour of other agents throughout the modelled system. Furthermore, it can be seen that the positive feedback seen as a result of the influence of social networks on the migration process is sensitive to demography as the numbers of individuals of an age where migration is a commonly adopted livelihood strategy increase. Thus, these results show that when population growth is non-zero, a climate-change signal in migration seems to emerge and, as population growth increases, the impact of climate change on migration is enhanced.

The development of an agent-based model investigating the impact of rainfall variability on migration serves as a heuristic device to understand the characteristics of aggregate migration behaviour in response to climate change and variability. Migration linked to climate change has been variously described as a complex and multifaceted phenomena with environmental changes affecting vulnerable communities through many and varied channels. Here, we show that within the complex adaptive system of climate and

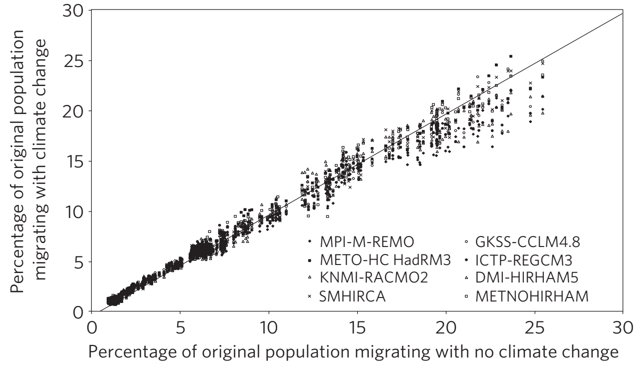


**Figure 3 | Simulated relationship between the percentages of the original population that migrates under future climate change compared with present climate conditions.** Simulations were produced under a range of demographic scenarios as defined by the United Nations, Department of Economic and Social Affairs, Population Division.

migration, the low-level influences of demography can combine with the impact of climate on individual behaviour to produce nonlinear and emergent changes in total migration that are not apparent when only climate change is considered.

## Methods

The migration decision of agents comprises three core components; behavioural attitude ($BA$), subjective norm ($SN$) and perceived behavioural control ($PBC$). To develop a preferred course of action in response to the rainfall conditions affecting an individual, each agent will score the five active options available to them (migrate to one of the four other zones, or migrate internationally) on the basis of these core components.

The $BA$, $SN$ and $PBC$ values calculated by agents contribute to their behavioural intention ($I$) towards the migration option being considered. As shown in equation (1), an individual agent's behavioural attitude is adjusted according to the combined impact of their networked peers ($SN$) and their perception of whether or not they have the assets/experience necessary to undertake the migration ($PBC$). Agents carry out an intention calculation for each of the migration adaptation options available to them:

$$I = (BA \times SN) \times PBC \tag{1}$$

In their development of a final intention towards a favoured course of action, an agent scores each of the options available to them. Although equation (1) appropriately represents the intention formation undertaken by an individual agent, when the process of developing behavioural intentions is undertaken in the model by a large cohort of agents, the equation used to determine intention values is altered to represent the likelihood of an individual within the reduced cohort of agents who decide they can afford to invest in migration, migrating. By identifying the population agents that perceive the migration to be possible ($PBC.pop$) an additional component is incorporated into the model as per the conditional term shown in equation (2):

$$\textbf{FOR ALL}\ I,\ PBC\ \textbf{IN}\ Agent$$
$$((BA \times PBC.pop) \times SN == \textbf{IF}\ PBC/=0\ \textbf{THEN}\ I\ \textbf{ELSE} == \mathbf{0}) \tag{2}$$

The conditional term above therefore states that if $PBC$ is not equal to zero, then $I$ is equal to the multiplication of $BA$, $PBC.pop$ and $SN$. However, on the condition that $PBC$ is equal to zero, the multiplication process is void and the $I$ value returned by the agent for that option is zero.

***PBC.*** Reducing $PBC$ to a value termed behavioural control ($BC$) which, developed using an asset rate ($ar$) and experience rate ($er$), represents the components considered by an agent in their perception of the control they have over their behaviour, allows the initial stage of $PBC$ formation to be undertaken on the basis of equation (3):

$$BC = ar + er \tag{3}$$

Following an agent's calculation of a $BC$ value towards the migration option being considered, the agent's $PBC$ score is calculated using the conditional term shown in equation (4):

$$\textbf{FOR ALL}\ rn, BC, PBC\ IN\ Agent$$
$$(1 == \textbf{IF}\ rn <= BC\ \textbf{THEN}\ PBC\ \textbf{ELSE} == \mathbf{0}) \tag{4}$$

If a random number ($rn$) between zero and one generated by the model is less than the resulting $BC$ value, a score of 1 is therefore allocated to $PBC$, migration is perceived by the agent to be within their means and an individual agent would develop an intention value towards that option. Otherwise a value of 0 is assigned to $PBC$ and an individual agent's intention to migrate will be zero. The agents' perceptions of their $BC$ return a binary outcome to aid clarification of the migration decision. Rather than an agent thinking they might have the capability to migrate, their consideration of an option is defined as a yes/no decision formed on the basis of assets and experience.

***BA.*** The $BA$ component of the decision to migrate represents the probability of an agent from origin location ($l$), with rainfall conditions ($rc$) that year and with present age ($a$), gender ($g$) and marital status ($s$) attributes, migrating to the destination option ($o$) being considered. The probability value ($PV$) of an agent migrating to $o$ is calculated from the number of individuals within the EMIUB data with defined attributes $a$, $g$ and $s$ who are migrants ($m$) from $l$, under the prevalent $rc$ in the period 1970–1979, divided by the population ($p$) of that location with the same defined attributes at that point in time (equation (5)):

$$PV_o(a,g,s,l,rc) = \frac{m(a,g,s,l,rc)}{(a,g,s,l)} \tag{5}$$

***SN.*** The purpose of the $SN$ component of an agent's decision to migrate is to incorporate the influence of an individual's peers on their development of behavioural intentions. Working with the information and data available to this research the $SN$ component of the decision to migrate is derived as a function ($f$) of an agent's consideration of the opinions of their networked peers ($po$; equation (6)). Each agent in the model is linked to fifty others through a simple network defined at model startup. Networked agents pass messages between themselves that inform one another of their most recent migration decisions. On the basis of the messages received by an agent, peer opinion values are derived for each of the migration options being considered:

$$SN = f(po) \tag{6}$$

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## Author contributions

All authors contributed extensively to the conception of the ABM and the analysis of the results. C.D.S. built and tested the ABM and D.R.K. wrote the bulk of the paper.

## Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to D.R.K.