

Climate change and internal migration patterns in Bangladesh: an agent-based model

BEHROOZ HASSANI-MAHMOOEI

Department of Econometrics and Business Statistics, Monash University, Melbourne, Victoria VIC3800, Australia.

Email: behrooz.hassani.mahmoei@monash.edu

BRETT W. PARRIS

Department of Econometrics and Business Statistics, Monash University, Australia. Email: brett.parris@monash.edu

Submitted 15 November 2011; revised 31 May 2012; accepted 1 July 2012; first published online July 27, 2012

ABSTRACT. Bangladesh is one of the countries most vulnerable to climate change impacts such as extreme weather events, due to its low-lying topography, high population density and widespread poverty. In this paper, we report on the development and results of an agent-based model of the migration dynamics that may arise in Bangladesh as a result of climate change. The main modules are each calibrated with data on relevant indicators, such as the incidences of extreme poverty, socioeconomic vulnerability, demography, and historical drought, cyclone and flood patterns. The results suggest likely changes in population densities across Bangladesh due to migration from the drought-prone western districts and areas vulnerable to cyclones and floods in the south, towards northern and eastern districts. The model predicts between 3 and 10 million internal migrants over the next 40 years, depending on the severity of the hazards. Some associated policy considerations are also discussed.

1. Introduction

It is so hard to live here. Everyday something happens. Who do we blame if there is a storm? There is nothing to do but find another home. How long can we go on living like this? (Interview with a village elder from Bangladesh – Kartiki, 2011)

Over the last 20 years, Bangladesh has experienced significant socioeconomic improvements (General Economics Division, 2009) but it is still categorized among the UN-designated Least Developed Countries (LDCs),

This paper benefited from discussions with Professor Brett Inder and Dr Simon Angus and comments from two anonymous referees. It was partially supported by a Faculty Pilot Grant received from the Faculty of Business and Economics at Monash University.

ranked 146 on the Human Development Index (United Nations Development Programme, 2011), with around 40 per cent of the population reported to be living in poverty, and almost half of the residents with no education (Bangladesh Bureau of Statistics, 2005).

Located at the top of the Bay of Bengal, between 20–26° North and 88–92° East, Bangladesh has been called a ‘country made for disasters’, due to its specific geographical characteristics and its current and anticipated vulnerabilities to climate risks (Poncelet *et al.*, 2010). Almost 80 per cent of the country is floodplains and on average 20 per cent of its area is flooded every year (Monirul Qader Mirza, 2002; Agrawala *et al.*, 2003).

There is a consensus in climate model outputs that Bangladesh will experience increases in temperature in the coming decades. Most of the climate models also predict that precipitation will increase, although seasonal differences are expected (Agrawala *et al.*, 2003) which can have severe consequences for a country where around 60 per cent of its citizens are directly and indirectly dependent on agricultural employment and production. The German Advisory Council on Global Change (2007), among others, believes that glacial retreats, annual monsoon variations, sea-level rise and cyclones could be sources of social crises and instability in India, Pakistan and Bangladesh. The vulnerability of Bangladesh to sea level rise, whether directly or through storms and cyclones, has also been acknowledged by many authors (e.g., Ali, 1996; Dasgupta *et al.*, 2009, 2011).

Considering the environmental and socioeconomic challenges that Bangladesh faces, numerous studies have shown that migration, whether voluntary or forced, temporary or permanent and internal or external, has been one of the main features of life in the region since the 18th century (Siddiqui, 2003; Joarder and Hasanuzzaman, 2008).

The Bangladesh Bureau of Statistics provides data showing how the number of net out-migrants increased dramatically from 212,000 in 1970 to 1,033,000 in 1990 and to 2,908,000 in 2010, with significant differences in patterns across genders. The net out-migration (emigrants/1,000 population) rose in both rural (1.5 to 4) and urban (1.2 to 16.4) areas between 1984 and 1998 (Bangladesh Bureau of Statistics, 2000, 2001, 2011). As can be seen in figure 1, the most recent data (Bangladesh Bureau of Statistics, 2009) shows that the levels have varied between 2003 and 2009, but on average they are considerably higher than the last couple of decades of the 20th century.

Various reasons have been proffered for the internal migration dynamics in Bangladesh, such as: (1) the high rate of urbanization, especially after the liberation of Bangladesh from Pakistan, which affected the sex ratio around the country as the males were more likely to migrate individually to the big cities; (2) lack of full-year employment and unoccupied arable land in rural areas; (3) environmental and climatic variations; and (4) higher wages at the destinations, which have led to multi-locational households and increasing levels of dependency on remittances (Jansen, 1987; Toufique, 2002; Afsar, 2003; Hossain *et al.*, 2003).

In this paper, we have used an agent-based model (ABM) with Bangladesh district-level data, to explore the possible migration dynamics across the country based on projected climate change scenarios. To our

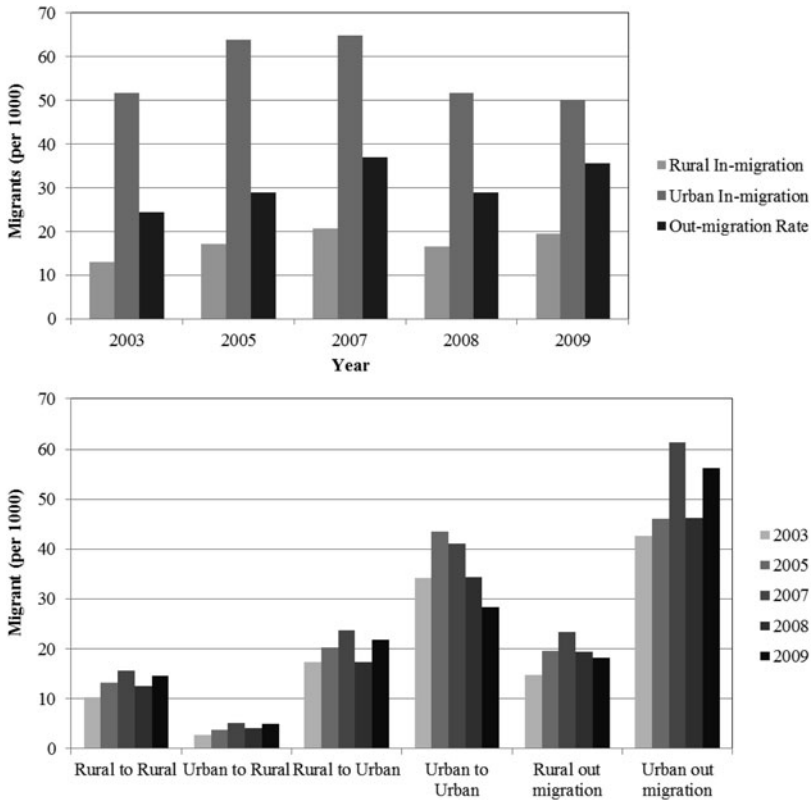


Figure 1. *Decomposition of Bangladesh migration flows*
 Source: Bangladesh Bureau of Statistics (2009).

knowledge, it is one of the first times that an ABM has been applied for this purpose at this scale and level of disaggregation. Using an ABM provides an opportunity for constructing an integrated migration model that is sensitive to social, economic and environmental factors, capable of considering heterogeneity among migrants and in migration dynamics, and capturing some of the complexity involved in the emergence of migration patterns.

Prior to this study, Silveira *et al.* (2006) applied a computational model to explore the urban–rural dynamics in developing countries. Kniveton *et al.* (2011) later developed an ABM to study the link between climatic change (in the form of rainfall), socioeconomic and political factors and migration, under different scenarios in Burkina Faso. They concluded that climate change is likely to play a significant role in shaping migration patterns in the coming decades.

In section 2 we briefly review the literature on the climate–migration link and provide details on the micro-level migration decision-making process in Bangladesh. In section 3 the model is introduced. The results are presented in section 4 and the conclusions in section 5.

2. Climate, migration and Bangladesh

The literature on climate-change induced migration has reached mixed conclusions (Myers, 2002; Kniveton *et al.*, 2008). Some authors believe that sudden or gradual impacts of climate change, such as a higher frequency and intensity of droughts, is likely to lead to mass-migration around the world, while others reject this claim or doubt the predicted scales, referring to people's adaptability and some international evidence on the relationship between past climate events and migration.

Warner and her colleagues believe that, as an alternative to adaptation or to accepting a lower living standard, migration is an important option for residents of the affected areas. In their perspective, the migration decision itself is affected by different socioeconomic and even political conditions (Warner *et al.*, 2010). Reuveny (2007) provides theoretical arguments and case studies on how climatic and environmental factors can lead to migration. He predicts that migration would be more likely in countries with lower levels of development, even causing conflict between the migrant and the receiving communities. Black *et al.* (2011) applied an integrated assessment approach to show how the current migration flows may vary in future due to changes in climate.

Conversely, some studies argue that climate variations, even in poor or developing countries such as Burkina Faso and Brazil, are not associated with increases in migration or at least show mixed responses (Henry *et al.*, 2004; Barbieri *et al.*, 2010). Naudé (2010) found no significant associations between natural disasters and resource scarcity, and international migration, for 45 sub-Saharan countries.

Raleigh and Urdal (2007) attempted to decompose the climate-induced migration patterns in developing countries, based on the differences in factors (e.g., gradual and sudden) and types of migration (internal, external, temporary and permanent) and concluded that no mass-migration would be likely to happen if human reactions and adaptations are considered, although between 0 and 30 per cent of temporary migrants are expected not to return to their places of origin.

Some authors believe that the environmental and socioeconomic factors behind migration cannot be separated (Lonergan, 1998; Kartiki, 2011). Others warn against the rhetorical use of terms such as 'climate refugee' (Hartmann, 2010). Brown (2007) contends that, although climate has affected human movements over history, migration is not the first response.

The climate-migration link seems to be more robust in Bangladesh where it was reported that in the mid-1980s close to two-thirds of households were displaced at least once in their lifetimes (Zaman, 1991). The majority of studies have predicted significant movements of people in Bangladesh, which has often been described as a hotspot case study by different authors, citing its low adaptation capacities and likely severe climate change impacts (Agrawala *et al.*, 2003; Hunter, 2005; Brown, 2007; Kniveton *et al.*, 2008; Perch-Nielsen *et al.*, 2008).

Alam (2003) reports that land and water scarcity in rural areas has caused inequality in employment opportunities and income, motivating internal and international migration among Bangladeshis. Internal migration,

moreover, is more likely to be undertaken by poorer households who are not able to pay to cross the border (Mendola, 2008).

Swain (1996) argued that floods and sea level rise would be the key drivers of migration in Bangladesh, and Hunter (2005) emphasized the role of floods and cyclones, noting that, although they may only cause temporary migration, even such temporary migration could contribute to civil disorder. Kartiki (2011) also describes migration as a resilience strategy against climate change in Bangladesh.

Sharma and Hugo (2009) review multiple studies and show how environmental factors have gained importance (as high as 40 per cent) in the internal migration decision process in Bangladesh. In their review, physical factors 'included, but were not limited to, storms, salinity, river erosion, land degradation, loss of land due to flooding and other environmental hazards'. They also predict that higher sea levels, increasing temperature and coastal damages and salinity and changes in the precipitation and flooding would bring further migration responses in the country.

Besides those mentioned above and some other studies that are introduced in the next section confirming the climate-migration link in Bangladesh, it should be mentioned that at least one paper, Paul (2005), discussed a 2004 tornado in north-central Bangladesh which destroyed 3,400 homes across 38 villages, killing more than 100 people. The tornado apparently did not cause migration, in part because of the role of proper emergency responses.

3. Data and model

In order to explore the possible climate-induced migration patterns in Bangladesh, we have implemented an ABM which is based on data from Bangladesh at the district level.

The decision to use an ABM is based on the fact that the migration literature has always struggled with the complexity of the issue. Initially the focus was primarily on the socioeconomic aspects, but increasingly attention has turned to the ecological and climatic dimensions as well (Hunter, 2005; Brown, 2007; Warner *et al.*, 2010). Researchers in a variety of fields have sought new approaches to model complex adaptive systems (Boccaro, 2004; Rosser, 2009; Xepapadeas, 2010) and ABMs have emerged as a promising research stream (Epstein, 2006; Tesfatsion, 2006). patterns in Bangladesh are significantly heterogeneous across the country (Kuhn, 2002) and are influenced by multiple causal pathways – factors that play to the strengths of an agent-based approach.

Bangladesh is divided into seven major administrative regions called divisions. Each division is divided into several districts (zilas), with 64 districts in total, with areas ranging from 716 km² (Meherpur) to 6,116 km² (Rangamati), which then are partitioned into 500 upazilas. In this paper, we have used the district-level data, as more disaggregated data at the upazila level were not available for many variables. Each district is represented in the model by one main agent who manages the interactions within the district and reports the results. The districts are connected together as a network with nodes representing the centroids of the districts

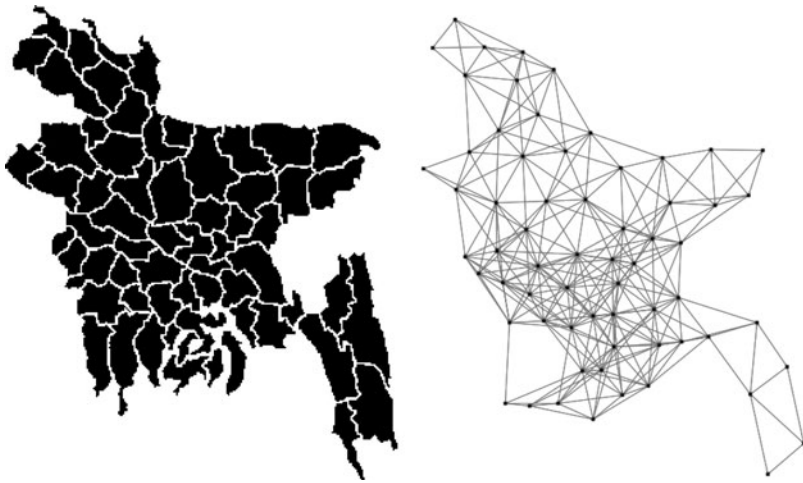


Figure 2. Bangladesh districts and district network structure (after Angus *et al.* 2009)

and links representing possible migration paths between districts. All districts are connected to the network, but they are only directly connected to those neighbouring districts with which they share a common boundary. Bangladesh's districts and the associated district network are shown in figure 2, following Angus *et al.* (2009).

The list of micro-level data items, their format and their sources are presented in table 1. The data for each district was downloaded separately from the Bangladesh Bureau of Statistics website¹ and the selected items extracted.

3.1. Migration decision

In common with most of the literature, the migration decision function is associated with three groups of factors in this model, including: (1) push factors – climate change scenarios and their possible impacts, and the socioeconomic conditions of each district such as poverty level, local government development expenditures and unemployment rate; (2) pull factors – socioeconomic conditions of the potential destinations; and (3) intervening factors – land or house ownership and employment conditions.

Table 2 provides a list of the heuristic rules that have been inferred from different micro-level studies on the factors affecting migration decision in Bangladesh. The rules are usually provided by authors based on local surveys.

3.2. Overview, design and details

In order to represent the model details, we have used the Overview, Design and Details protocol (ODD) which recently has been widely used for describing ABMs (Grimm, 2006; Grimm *et al.*, 2010).

¹ The URL is <http://www.bbs.gov.bd/>.

Table 1. Data titles and sources

Title	Type	Source	Factor group
<i>The model's environment</i>			
Bangladesh Map	Map	Constituency Maps of Bangladesh	
<i>Climate layers</i>			
Sea-level rise	Map/scenario	Agrawala <i>et al.</i> (2003) Yu <i>et al.</i> (2010)	
Floods and droughts	Map/scenarios	Parry <i>et al.</i> (2007)	Environment
<i>Demographic variables</i>			
District population		BBS (2001)	
Density	per km ²	BBS (2001)	
Religion	Percentage	Zila Series, 2001, BBS	Ethnicity
<i>Development variables</i>			
Poverty	Map	World Bank (2005)	Economy
MDG achievement	Order	UNICEF (2010)	Economy
Literacy level	Percentage	Zila Series, 2001, BBS	Education
Number of pri- mary schools/ population		Zila Series, 2001, BBS	Education
Doctors/population		BBS (2001)	Health
Houses with toilet	Percentage	Zila Series, 2001, BBS	Health
Banks/population		BBS (2001)	Infrastructure
Telephone/ population		Zila Series, 2001, BBS	Infrastructure
<i>Economic variables</i>			
House ownership	Percentage	Zila Series 2001, BBS	Intervening
Land ownership	Percentage	Zila Series 2001, BBS	Intervening
Employment	Percentage	Zila Series, 2001, BBS	Intervening and economy

Source: Bangladesh Bureau of Statistics (BBS).

Purpose

The purpose of the model is to study the possible population migration dynamics in Bangladesh due to extreme climatic and environmental shocks.

State variables and scales

The main entities of the model include the Time, District Agent (District), the representative Individual Agent (Agent), and Scenarios. The smallest

Table 2. *Observed migration decision rules*

<i>Rule</i>	<i>References</i>
Migrants would prefer closer destinations to avoid travel costs and to be able to return to their homeland in future.	Zaman (1991) Joarder and Hasanuzzaman (2008)
Migrants who do not own agricultural land or who have smaller plot sizes have more interest in migration.	Kartiki (2011) Kuhn (2005)
Lack of optimism about village improvement and rebuilding encourages migration.	Kartiki (2011)
People migrate to places where they have family or friends.	Kartiki (2011) Ahmed (2009)
Migrants prefer to migrate to urban areas.	Kartiki (2011)
Migrants with higher levels of wealth are more reluctant to migrate; land access can be used as a proxy for wealth.	Kuhn (2005)
People with higher education levels are more likely to migrate.	Kuhn (2005) Ahmed (2009)
Migrants would prefer to move to more developed areas.	Ahmed (2009)
Unemployed people are more likely to migrate.	Hossain (2001)
People with non-agricultural jobs are more likely to migrate.	Hossain (2001)

temporal unit is one tick, representing one month, and the model is run for 50 years. Each of the 64 District Agents represents one district. District Agents store the district's features such as its socioeconomic development level and also update some variables such population and its density.

Each Individual Agent represents 10,000 people and the model initiates with 12,317 agents distributed across the 64 districts, representing the total estimated 2001 population of 123,170,000 people. This level of abstraction has been chosen to ensure that all the attributes which characterize more than 1 per cent of the population have at least one member to represent them in the simulated environment. Since the lowest agent population in any district is 29 when the model starts, it means that one agent is representing at most 3 per cent of a district's population. On average, each agent represents 0.7 per cent of a district's population.

Population growth in Bangladesh, as with any other country, is affected both by natural factors such as birth rate, death rate and family size and by inward- and outward-migration flows. Since we want to reproduce the combined effect of these two sets of factors which together produce the population growth rate, we avoided simply using the observed growth numbers. Instead, as the birth and death rates are not available, the household size is used to determine natural population growth across the districts. Every 12 ticks (at the end of every year), each district's population increases by a multiple of that district's household size. For instance, if a district has 100 agents (representing 1,000,000 people) and its average

household size is 5.6, its population increases by $(5.6 - \beta_1) \times \beta_2$, where β_1 and β_2 determine the population growth scenario and can be calibrated to provide different population trends. In the simulations presented, β_1 is set to 1 and β_2 is set to 0.03 to provide a 'fertility remains constant' scenario. So for this sample district, at the end of that year the district's population increases by 14 agents, rounding $(100 \times (5.6 - 1) \times 0.03)$. The values of these variables and the scale of representation are selected in such a way as to ensure that at least one agent is added to the district every year. The model endogenously generates the migration component. This has been done to avoid applying the population growth rate directly to the model, and instead using a proxy which can represent the population growth rate differences between the districts.

The agents do not die since net population growth has been used in the model. Each agent has a migration threshold which is used to represent its resilience against the push factors. The concept of threshold has been widely used in the migration literature before (Hunter, 2005), and we believe it provides a better insight into the complex migration behaviour of agents than neoclassical migration models that are based simply on cost-benefit analyses.

Each climate scenario is a time series with 600 data points (50 years \times 12 months), each a number between 0 and 1, produced by a Poisson distribution given by:

$$climate_{it} = random\text{-}poisson(1 + time/600) \times env_i \tag{1}$$

where $climate_{it}$ represents the intensity of the climatic shock for district i at time t and $(time/600)$ provides an increasing trend for shock occurrence probability; env_i guarantees that the scenarios are localized, based on historical climatic data for each district to produce separate scenarios across the country. The variable env_i is a continuous variable with values between 0 and 1, which takes into account the combined impacts of droughts, floods, cyclones and sea level rise and is distributed across the 64 districts as shown in figure 3. If the env_i is equal to 0, it means that specific district i is not vulnerable to any kind of climatic event, while if it is 1 it means that the district has the highest level of exposure among all 64 districts. As can be seen in figure 3, while the value can be between 0 and 1, it is mainly distributed under 0.35, confirming that districts have heterogeneous level of vulnerability.

According to the Poisson distribution, if λ is the expected number of events in a given time interval, then the probability that there will be exactly x occurrences is equal to:

$$f(x, \lambda) = \frac{\lambda^x e^{-\lambda}}{x!} \tag{2}$$

When the model starts, at $time = 1$, λ is very close to 1 and so the probability of a climatic event for different values of x will be very low when compared to agents' thresholds where λ is 3. Over the course of the simulation, as $time$ increases incrementally, the random-Poisson function produces greater values, leading to an increase in the probability of a climatic shock.

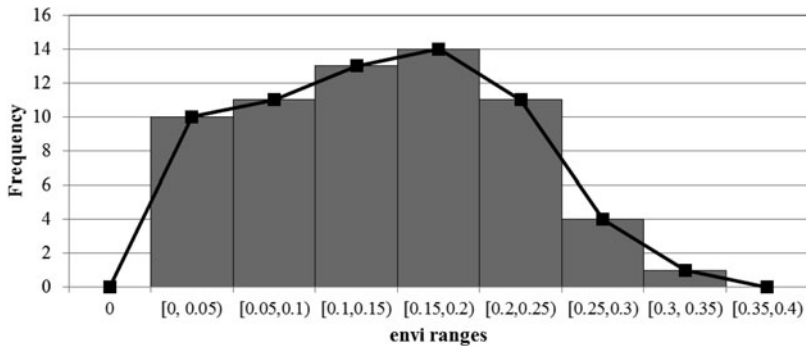


Figure 3. Distribution of env_i over 64 districts. env_i which is between 0 and 1 represents each district's vulnerability to different climatic events. Districts with higher env_i values are expected to be more affected by climate change consequences

The Poisson distribution and associated λ values were selected to avoid frequent severe climatic shocks. The final impact scenario is the average of all three threads and is called Impact (I) where each item is a value between 0 and 1 and shows the intensity of incidence. Over time both the intensity and frequency of the climatic shocks increase as λ increases to 2.

Process overview and scheduling

A sample process for an agent is shown in figure 4. During every tick, each agent considers the push and intervening factors and makes a decision on its migration. If it decides that migration could be beneficial, it measures the pull factors for all the districts in its 100-km radius² and then moves to the closest district with the best socioeconomic conditions which is chosen in accordance with equation (4), described below. As temporary migration usually only occurs within a short range from the original location (Zaman, 1991; Joarder and Hasanuzzaman, 2008), agents do not leave their current districts and so they are ignored in this model.

Design concepts

The main sources of emergence in the model are the preferences and interactions at the individual level which lead to the migration flows between the districts. The agents' adaptation decisions are based on their individual parameters and their perceptions about their social networks, trying to decrease their vulnerability and improve their socioeconomic conditions as their objective. Agents learn by considering their stay/migration decision outcomes in the past and using them as inputs through a feedback loop for their future decisions. As a result, when migration improves an agent's socioeconomic status, on the one hand the agent will be more inclined to migrate in future, which works as a positive feedback. But on

² We also tested for 200- and 300-km radii and the results did not change significantly.

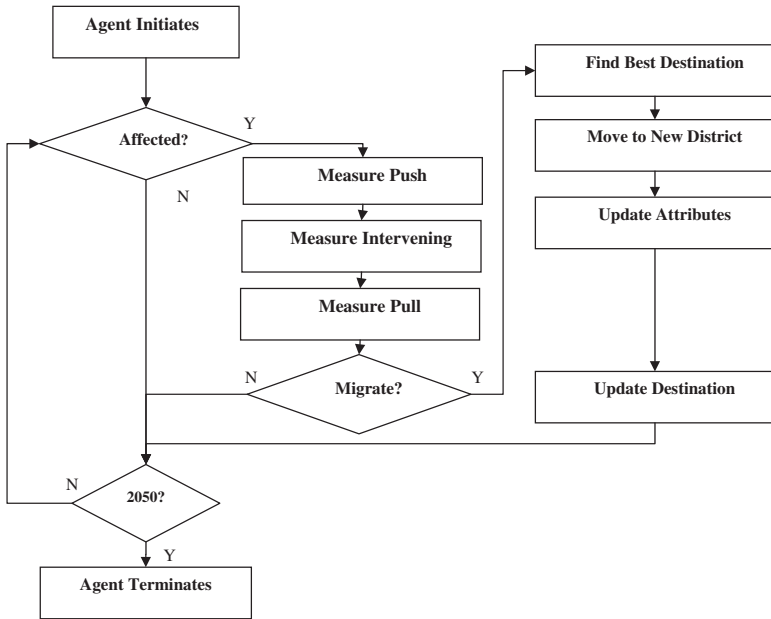


Figure 4. Process overview for a sample agent

the other hand, an improvement in the agent’s attributes, such as employment or land ownership, may make migration less likely. The effects on the intervening factors in such a case function as a negative feedback, dampening any increased inclination to migrate. Also, a negative feedback exists at the macro level: when more agents migrate to a specific district, that can decrease the destination’s favourability for future migrations, since population density increases and less land and jobs are available.

The main external factors that agents sense include the changes in the climate, the changes in the socioeconomic conditions in the current position and destination, and their social network performance which provides the individual-level interactions. The main recorded outcomes for the model include the most favoured movement paths and also the final distribution of population around Bangladesh.

Mathematical skeleton

The intervening factor (*inter*) is a random variable distributed uniformly between 0 and 1, associated with house and land ownership and employment. Since there is no study measuring migration decision sensitivities to house and land ownership and employment status, we have used a module which is constructed using three uniformly randomly distributed values, as equation (3).

$$inter_i = random H_{ij} + random L_{ij} + random E_{ij} \tag{3}$$

Table 3. Sample intervening factor values

	House ownership (H_{ij})	Land ownership (L_{ij})	Employment (E_{ij})
Yes	Random uniform (0,0.25)	Random uniform (0,0.1)	Random uniform (0,0.1)
No	Random uniform (0,1)	Random uniform (0.5)	Random uniform (0,1)

where $inter_i$ is the intervening factor for agent i , H_{ij} represents his house ownership, L_{ij} is for land ownership and E_{ij} is employment. The j subscript can be either 1 if the agent owns any land, owns a house or is employed and 0 if he does not; the *random* function returns a random float value between 0 and its input value, a sample of which is presented in table 3. Agents who have a house, land, job or a combination of these have higher values of the intervening factor.

If *migrate* is greater than the agent's migration *threshold*, then it will migrate to the neighbouring district with the highest *pull* factor. The *pull* factor is a weighted function of socioeconomic and environmental conditions at the possible destination districts.

$$pull_{ij} = \alpha_{1j}EC_i + \alpha_{2j}ED_i + \alpha_{3j}EN_i + \alpha_{4j}ET_i + \alpha_{5j}IF_i + \alpha_{6j}HE_i + \alpha_{7j}(1/DI_{ij}) \quad (4)$$

The *pull* factor of district i for agent j is a function of EC which represents economic variables, ED for education, EN for environmental, ET for ethnic composition, IF for infrastructure, HE for health and DI for mutual distance, where $\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \alpha_6 + \alpha_7 = 1$. To create the alphas each agent first produces seven random numbers between 0 and 99 (r_i) and then $\alpha_i = r_1 / \sum_{j=1}^7 r_j$.

4. Implementation and results

The model was implemented in NetLogo 4.1 (Wilensky, 1999), run on Monash University's Sun Grid High Performance Computing cluster, and the results were analysed using R (R Development Core Team, 2011). NetLogo uses a pseudo-random system, which means that, while the random numbers are 'random', their generation process is deterministic, based on an initial 'seed' number which is fed to the random number-generating algorithm. So, by choosing the same seed in different simulations, the final produced output of numbers will be the same, but selecting different seeds leads to generating different sets of initial conditions and therefore different results. All the experiments were run 20 times (seeds 1–20) to avoid possible dependencies on initial or run-time conditions and to provide Monte Carlo data.

The Monte Carlo simulation provides different distribution setups in every model run. For instance, if in one district with 1,000 agents where

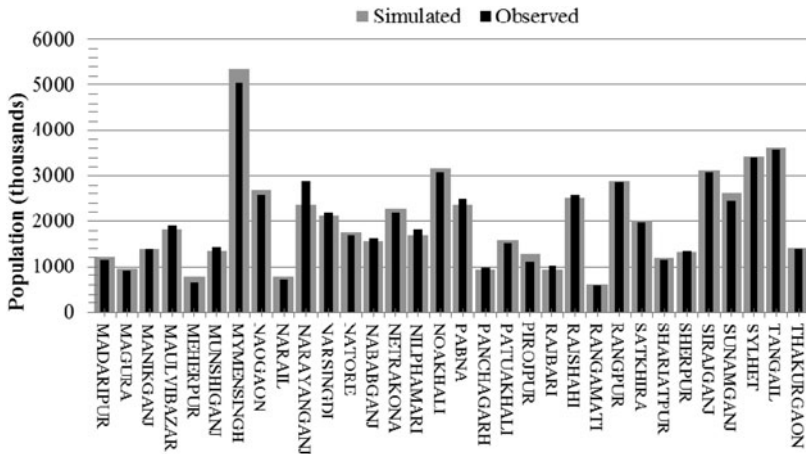


Figure 5. Model population at 2011 vs. observed 2011 population for 32 districts

90 per cent of the population is Muslim and 65 per cent are land-owners, then in this specific district all Muslim agents may own their land, so we would have 650 Muslim land-owners, 250 Muslims without land and 100 non-Muslims without land. On the other hand, it could be 100 non-Muslim land owners, 550 Muslims with land and 350 Muslims without land. As individual-level data is not available to find out exactly how the attributes should be distributed, the random seeds in the Monte Carlo simulation generate different initial conditions and the final average results are not dependent on a specific distribution.

We first ran the model for 10 years (2001–2010), 20 times (seeds 1–20), and validated the population projection with the recently published primary results of the Bangladesh 2011 Population and Housing Census (Bangladesh Bureau of Statistics, 2011). Figure 5 shows the estimated and real populations for 32 districts.³

As can be seen, in many cases our predictions are close to the observed values, although for a few districts such as Ganjipur, which has experienced the highest population growth over the past 10 years in Bangladesh (60 per cent in a decade), the model performance is poorer. In the final model, the average difference between the observed and the simulated district populations for 2011 is 2.42 per cent of the observed populations. The only variables adjusted are the intervening factor components, E_{ij} , L_{ij} and H_{ij} , whose final values are presented in table 3.

4.1. Simulation outputs

Figure 6 shows the expected changes in population density in Bangladesh over the next 40 years based on the simulation outputs. The model’s population for 2050 is around 295 million which is in line with the official

³ For space reasons only the latter 32 districts in alphabetical order are shown. The results for the first 32 districts were similar.

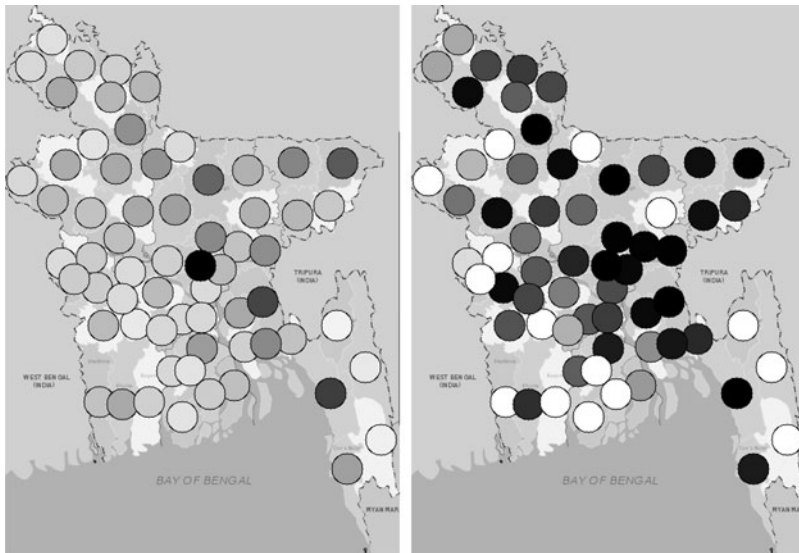


Figure 6. Projected changes in each district's population (left) and population density (right) for 2050. The darker circles show higher values. The black circle in the left map shows Dhaka

Bangladesh population projections of 294.38 million, based on 'fertility remains constant' scenario (Bangladesh Bureau of Statistics, 2006).

According to the model outputs, it is projected that most Bangladeshis would live in the central and eastern parts of the country, namely Sylhet, Dhaka and Chittagong divisions, partly driven by the droughts in the western areas and the continual flooding in the southern districts. The model predicts between 3 and 10 million migrants over the next 40 years, depending on the scenario.

The model predicts that migrants would gravitate not only to the already populated urban areas, but also to Jhenaidah in the west and Comilla in the east and Gaibandha in the north, at least for temporary residence. These three districts are likely to be attractive due to their weaker sensitivity to adverse climate impacts, since they are in areas less vulnerable to sea level rise, or they are less likely to be affected by future droughts or floods.

5. Conclusion

Due to its geographic and economic characteristics, Bangladesh is among the countries most vulnerable to climate change impacts. In this paper, we used an ABM, implemented using real-world data, to explore the possible migration patterns in Bangladesh due to climatic shocks such as droughts, floods and cyclones.

The results show that climate change would be likely to affect migration within Bangladesh, by increasing movements towards the east and north-east districts, which are less affected by droughts and floods. The model

also suggests that the current urban areas will continue to absorb migrants, and the environmentally vulnerable cities such as Dhaka will need to provide more non-agricultural jobs, such as manufacturing and commerce, in order to be able to accommodate the coming migrants.

Difficult adaptation funding choices may need to be made in future between either local-level climate adaptation initiatives, such as flood control in vulnerable districts, or providing affordable housing, land and services, and fostering employment for migrants moving from areas judged by residents to be too hazardous to remain in. The authors believe that further empirically grounded research along the lines presented in this paper can be used to suggest the districts most likely to witness an influx of internal migrants. Such projections may assist the national and district governments in Bangladesh to manage and prepare for future migration flows, thereby improving the country's adaptation to climate change.

References

- Afsar, R. (2003), 'Internal migration and the development nexus: the case of Bangladesh', Paper presented at the *Regional Conference on Migration, Development and Pro-Poor Policy Choices in Asia*, 22–24 June, Dhaka, Bangladesh.
- Agrawala, S., T. Ota, A.U. Ahmed, J. Smith, and M. van Aalst (2003), 'Development and climate change in Bangladesh focus on coastal flooding and the Sundarbans', Organisation for Economic Co-operation and Development, Paris, France.
- Ahmed, I. (2009), 'Environmental refugees and environmental distress migration as a security challenge for India and Bangladesh', in H.G. Brauch, Ú.O. Spring, J. Grin *et al.* (eds), *Facing Global Environmental Change*, Berlin and Heidelberg: Springer-Verlag, pp. 295–308.
- Alam, S. (2003), 'Environmentally induced migration from Bangladesh to India', *Strategic Analysis* 27(3): 422–438.
- Ali, A. (1996), 'Vulnerability of Bangladesh to climate change and sea level rise through tropical cyclones and storm surges', *Water, Air, & Soil Pollution* 92(1): 171–179.
- Angus, S.D., B. Parris, and B. Hassani-M. (2009), 'Climate change impacts and adaptation in Bangladesh: an agent-based approach', Paper presented at the *18th World IMACS/MODSIM Congress*, 13–17 July, Cairns, Australia.
- Bangladesh Bureau of Statistics (2000), *Report of Sample Vital Registration System*, Dhaka: Ministry of Planning, Government of the People's Republic of Bangladesh.
- Bangladesh Bureau of Statistics (2001), *Population and Housing Census 2001*, Dhaka: Statistics Division, Ministry of Planning, Government of the People's Republic of Bangladesh.
- Bangladesh Bureau of Statistics (2005), *Household Income and Expenditure Survey*, Dhaka: Ministry of Planning, Government of the People's Republic of Bangladesh.
- Bangladesh Bureau of Statistics (2006), *Sectoral Need-based Projections in Bangladesh*, Dhaka: Planning Division, Ministry of Planning, Government of the People's Republic of Bangladesh.
- Bangladesh Bureau of Statistics (2009), *Bangladesh Sample Vital Registration System*, Dhaka: Ministry of Planning, Government of the People's Republic of Bangladesh.

- Bangladesh Bureau of Statistics (2011), *Population and Housing Census 2011 – Primary Results*, Dhaka: Statistics Division, Ministry of Planning, Government of the People's Republic of Bangladesh.
- Barbieri, A., E. Domingues, B. Queiroz, R. Ruiz, J. Rigotti, J. Carvalho, and M. Resende (2010), 'Climate change and population migration in Brazil's Northeast: scenarios for 2025–2050', *Population and Environment* **31**(5): 344–370.
- Black, R., D. Kniveton, and K. Schmidt-Verkerk (2011), 'Migration and climate change: towards an integrated assessment of sensitivity', *Environment and Planning A* **43**: 431–450.
- Boccaro, N. (2004), *Modeling Complex Systems (Graduate Texts in Contemporary Physics)*, New York, Berlin and Heidelberg: Springer-Verlag.
- Brown, O. (2007), 'Climate change and forced migration: observations, projections and implications', Unpublished manuscript, Human Development Occasional Papers (1992–2007), HDOCPA-2007-17, Human Development Report Office, United Nations Development Programme, Geneva, Switzerland.
- Dasgupta, S., B. Laplante, C. Meisner, D. Wheeler, and J. Yan (2009), 'The impact of sea level rise on developing countries: a comparative analysis', *Climatic Change* **93**(3): 379–388.
- Dasgupta, S., B. Laplante, S. Murray, and D. Wheeler (2011), 'Exposure of developing countries to sea-level rise and storm surges', *Climatic Change* **106**(4): 567–579.
- Epstein, J.M. (2006), 'Remarks on the foundations of agent-based generative social science', in L. Tesfatsion and K.L. Judd (eds), *Handbook of Computational Economics*, Amsterdam: Elsevier, pp. 1585–1604.
- General Economics Division (2009), *The Millennium Development Goals – Bangladesh Progress*, Dhaka: Planning Commission, Government of the People's Republic of Bangladesh.
- German Advisory Council on Global Change (2007), *World in Transition: Climate Change as a Security Risk*, Berlin: Earthscan.
- Grimm, V. (2006), 'A standard protocol for describing individual-based and agent-based models', *Ecological Modelling* **198**(1–2): 115–126.
- Grimm, V., U. Berger, D.L. DeAngelis, J.G. Polhill, J. Giske, and S.F. Railsback (2010), 'The ODD protocol: a review and first update', *Ecological Modelling* **221**(23): 2760–2768.
- Hartmann, B. (2010), 'Rethinking climate refugees and climate conflict: rhetoric, reality and the politics of policy discourse', *Journal of International Development* **22**(2): 233–246.
- Henry, S., B. Schoumaker, and C. Beauchemin (2004), 'The impact of rainfall on the first out-migration: a multi-level event-history analysis in Burkina Faso', *Population and Environment* **25**(5): 423–460.
- Hossain, M.Z. (2001), 'Rural–urban migration in Bangladesh: a micro-level study', presented at the *International Union for the Scientific Study of Population Conference*, 20–24 August 2001, Brazil.
- Hossain, M.I., I.A. Khan, and J. Seeley (2003), 'Surviving on their feet: charting the mobile livelihoods of the poor in rural Bangladesh', Paper presented at the *Conference on Staying Poor: Chronic Poverty and Development Policy*, 7–9 April, Institute for Development and Policy Management, University of Manchester, UK.
- Hunter, L.M. (2005), 'Migration and environmental hazards', *Population and Environment* **26**(4): 273–302.
- Jansen, E. (1987), *Rural Bangladesh: Competition for Scarce Resources*, Dhaka: University Press Limited.
- Joarder, M. and S. Hasanuzzaman (2008), 'Migration decision from Bangladesh: permanent versus temporary', *Asia Europe Journal* **6**(3): 531–545.

- Kartiki, K. (2011), 'Climate change and migration: a case study from rural Bangladesh', *Gender and Development* 19(1): 23–38.
- Kniveton, D., K. Schmidt-Verkerk, C. Smith, and R. Black (2008), 'Climate change and migration: improving methodologies to estimate flows', Unpublished manuscript, IOM Migration Research Series No. 33, International Organization for Migration, Geneva.
- Kniveton, D., C. Smith, and S. Wood (2011), 'Agent-based model simulations of future changes in migration flows for Burkina Faso', *Global Environmental Change* 21(Suppl. 1): S34–S40.
- Kuhn, R.S. (2002), 'The logic of letting go: family and individual migration from rural Bangladesh', Unpublished manuscript, Working Paper No. PAC2002–0004, Population Aging Center, University of Colorado at Boulder, Boulder.
- Kuhn, R.S. (2005), 'The determinants of family and individual migration: a case-study of rural Bangladesh', Unpublished manuscript, Working Paper No. PAC2004–04, Population Aging Center, University of Colorado at Boulder, Boulder.
- Loneragan, S. (1998), 'The role of environmental degradation in population displacement', *Environmental Change and Security Project Report* 4: 5–15.
- Mendola, M. (2008), 'Migration and technological change in rural households: complements or substitutes?', *Journal of Development Economics* 85(1–2): 150–175.
- Monirul Qader Mirza, M. (2002), 'Global warming and changes in the probability of occurrence of floods in Bangladesh and implications', *Global Environmental Change* 12(2): 127–138.
- Myers, N. (2002), 'Environmental refugees: a growing phenomenon of the 21st century', *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* 357(1420): 609–613.
- Naudé, W. (2010), 'The determinants of migration from Sub-Saharan African countries', *Journal of African Economies* 19(3): 330–356.
- Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK and New York: Cambridge University Press.
- Paul, B.K. (2005), 'Evidence against disaster-induced migration: the 2004 tornado in north-central Bangladesh', *Disasters* 29(4): 370–385.
- Perch-Nielsen, S., M.B. Bättig, and D. Imboden (2008), 'Exploring the link between climate change and migration', *Climatic Change* 91(3): 375–393.
- Poncelet, A., F. Gemenne, M. Martiniello, and H. Boussetta (2010), 'A country made for disasters: environmental vulnerability and forced migration in Bangladesh', in T. Afifi and J. Jager (eds), *Environment, Forced Migration and Social Vulnerability*, Berlin and Heidelberg: Springer-Verlag.
- R Development Core Team (2011), *R: A Language and Environment for Statistical Computing*, Vienna: R Foundation for Statistical Computing.
- Raleigh, C. and H. Urdal (2007), 'Climate change, environmental degradation and armed conflict', *Political Geography* 26(6): 674–694.
- Reuveny, R. (2007), 'Climate change-induced migration and violent conflict', *Political Geography* 26(6): 656–673.
- Rosser, J.B. (2009), *Handbook of Research on Complexity*, Cheltenham and Northampton, MA: Edward Elgar.
- Sharma, V. and G. Hugo (2009), 'Exploring the population–environment nexus: understanding climate change, environmental degradation and migration in Bangladesh', Paper presented at the 26th International Union for Scientific Study of Population (IUSSP) Conference, Marrakech, Morocco.

- Siddiqui, T. (2003), 'Migration as a livelihood strategy for the poor: the Bangladesh case', Paper presented at the *Regional Conference on Migration Development Pro-Poor Policy Choices in Asia*, 22–24 June, Dhaka, Bangladesh.
- Silveira, J.J., A.L. Espindola, and T.J.P. Penna (2006), 'Agent-based model to rural-urban migration analysis', *Physica A: Statistical Mechanics and its Applications* **364**: 445–456.
- Swain, A. (1996), 'Displacing the conflict: environmental destruction in Bangladesh and ethnic conflict in India', *Journal of Peace Research* **33**(2): 189–204.
- Tesfatsion, L. (2006), 'Agent-based computational economics: a constructive approach to economic theory', in L. Tesfatsion and K.L. Judd (eds), *Handbook of Computational Economics*, Amsterdam: Elsevier, pp. 831–880.
- Toufique, K.A. (2002), 'Agricultural and non-agricultural livelihoods in rural Bangladesh: a relationship in flux', in K.A. Toufique and C. Turton (eds), *Hands Not Land: How Livelihoods are Changing in Rural Bangladesh*, Dhaka and London: Bangladesh Institute of Development Studies and Department for International Development.
- UNICEF (2010), *Key Findings of the Bangladesh Multiple Indicator Cluster Survey 2009: Preliminary Report*, Dhaka: Bangladesh Bureau of Statistics and United Nations Children's Fund.
- United Nations Development Programme (2011), *Human Development Report 2011. Sustainability and Equity: A Better Future for All*, New York: Palgrave Macmillan.
- Warner, K., M. Hamza, A. Oliver-Smith, F. Renaud, and A. Julca (2010), 'Climate change, environmental degradation and migration', *Natural Hazards* **55**(3): 689–715.
- Wilensky, U. (1999), *NetLogo*, Evanston: Center for Connected Learning and Computer-Based Modeling, Northwestern University.
- World Bank (2005), *Updating Poverty Maps Of Bangladesh*, Dhaka: Bangladesh Bureau of Statistics and the World Bank, in collaboration with the World Food Programme.
- Xepapadeas, A. (2010), 'Modeling complex systems', *Agricultural Economics* **41**: 181–191.
- Yu, W., M. Alam, A. Hassan, A.S. Khan, A. Ruane, C. Rosenzweig, D. Major, and J. Thurlow (2010), *Climate Change Risks and Food Security in Bangladesh*, London and Washington, DC: Earthscan.
- Zaman, M.Q. (1991), 'The displaced poor and resettlement policies in Bangladesh', *Disasters* **15**(2): 117–125.