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Sustainable Resilience and the Spill-Over Effect

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ABSTRACT

Developing nations incur a greater risk to overpopulation and climate stress than the developed world due to strained resource management, unreliable infrastructure and brittle governing/economic institutions. When fragile states are stressed these vulnerabilities are often manifest in a "domino effect" of reduced natural resource production−leading to economic hardship−followed by desperate emigration, social unrest, and humanitarian crises. The impact is not limited to a single nation or region but "spills over" to adjoining areas with even broader impact on global markets and security. As a first step toward understanding and analysing this spill-over effect, a framework for modelling human migration is needed. Here a model of human migration is introduced that is formulated in a manner analogous to the mechanistic model for diffusion. This conceptualization integrates three key factors contributing to migration, the push-pull effect between conditions at the point of origin and the preferred destination, adaptive capacity to migrate, as well as a risk appraisal to identify the population susceptible to migration.

KEYWORDS

Human Migration, Spill-Over, Theory of Planned Behaviour, Diffusion, Climate Change, Adaptive Capacity, Human Security

INTRODUCTION

Migration has been a part of the human endeavour since the beginning of time as evidenced by the broad distribution of peoples throughout the world. In the most simple of terms, people migrate in hopes of improving their quality of life [1]; however, the specific reasons for migration are many and varied. Several causal linkages have been suggested, including conflict [2,3], economy/employment [4], land degradation [5], social networks [6], community factors [7], and environmental disasters [8]. Rarely is a single factor to blame but rather multiple stressors acting together. This cause and affect aspect of human migration is often conceptualized as a "push-pull" relationship in which deteriorating conditions at the point of origin push the migrant out, while better conditions at the destination pull or attract the migrant away [1,9].

There are other factors influencing the dynamics of migration. Adaptive capacity acts as a reality check on physical migration. Adaptive capacity is the ability or capacity of a system to modify or change its characteristics or behaviour so as to cope better with existing or anticipated external stresses [10]. Adaptive capacity can take the form of financial resources to fund

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travel, passports/visas to facilitate border crossings, or simply a social network in the receiving location [11,12].

The expression of migration can be manifest in different ways depending on the timing, duration, spatial scope and purposefulness of the action [13]. That is, migration can be anticipatory or proactive, short term or long term, local or international, etc. The adaptive capacity and the perceived push-pull are influenced by the nature of the migration considered [14]. While far from exhaustive, this discussion helps to demonstrate that the choice to migrate is dependent on many interacting and dynamic factors.

The spectre of climate change has drawn recent attention to human migration, suggesting that intensifying floods, droughts, and sea level rise could result in unprecedented migration [15]. Projections of environmentally induced migration vary widely from 200 million [16] to 700 million [17] by 2050. While many may question these numbers, few disagree with the fact that such environmental challenges will put increased stress on at-risk populations to migrate. The potential seriousness of this issue along with the complexity of the problem points to the need for trusted quantitative tools.

Over the years a wide variety of models have been developed to address various aspects of human migration (briefly described below). Here, key elements from past modelling efforts are integrated in a unique manner to provide a new look at human migration. The model is cast in a form analogous to the physical process of diffusion. In this analogue migration moves in response to the relative difference in living conditions between locations (i.e., push-pull), similar to the action of the concentration gradient in the diffusion model. Likewise, migration is modulated by adaptive capacity in a manner similar to the diffusion coefficient in the diffusion equation.

Below the paper begins with a broad overview of mathematical modelling of human migration. This is followed by a description of the proposed diffusion model of migration. The paper is closed with a brief discussion of how the migration model fits within the broader spill-over model and on-going efforts to test and implement the model.

MODEL REVIEW

As noted above, many factors play into decisions concerning an individual's choice to migrate. This diversity of factors is one of the reasons that the dynamics of migration are studied from so many different perspectives [18]. The fact that different disciplines have different ways of approaching migration contributes to the lack of a consistent, common theoretical base for development [19]. In reviewing this literature, there are many different approaches that could be taken to classify and organize the range of migration models. Certainly the causal framework adopted varies considerably, generally moving from simple to complex. The manner in which the models are operationalized also varies, ranging from qualitative conceptual modelling, to empirically-based modelling, and finally complex agent based modelling. Given the breadth in migration modelling literature the intent is not to be exhaustive in the review of models, rather the interest is to provide a context for the later model development (see next section).

The conceptual basis for migration modelling was set in the 1880's by Ravenstein's seven laws of migration [1]. Lee [9] later provided a simple framework from which to explore migration. Migration was established as an individual's decision involving the comparison of the place of origin with the place of destination. Attracting, repelling and neutral forces are at play in shaping the individual's decision, and these forces are unique to that individual's perspective. Between the place of origin and destination are intervening obstacles that can be physical, social, or political in nature. In this sense, migration is envisioned as influenced by a push-pull process, modulated by the extent of intervening obstacles.

Conceptual modelling has continued to be used to qualitatively explain observed migration behaviour. Clear evolution in complexity is evident since the early work of Lee [9]. For example, McLeman and Smit [20] consider the response of community institutions to changing environmental conditions. Where the institutions are unable to cope with the change, individual households respond according to their own adaptive measures. Black and others take the next step by explicitly addressing the individual's choices in adaptive response as well as divide the drivers of migration into social, political, demographic, economic and environmental [21]. Using the severe drought of the 1930's in rural Canada, Gilbert and McLeman [22] incorporate ideas of adaptive capacity and competing adaptive strategies (i.e., changing farm practices, migration). With this model they examine how differential access to economic, social, and human capital influences the capacity of households to adapt to severe drought.

Empirical models have been widely utilized to examine issues of migration. The gravity model adopts a semi mechanistic approach, which treats migration as proportional to the population masses at the point of origin and destination, and inverse to the distance between the two locations [23]. Afifi and Warner [24] expand the gravity model to include economic, political, social, and historical/cultural factors while evaluating the statistical significance of the various factors through regression analysis. A theoretical model of environmentally induced migration was examined empirically with regression analysis [25]. Results showed that environmental decline plays a statistically significant role in out-migration using global data from the late 1980's to the 1990's. Using a multinomial logit model Massey and Espinosa [26] were able to show that Mexico-U.S. migration stems from three mutually reinforcing process: social capital formation, human capital formation and market consolidation. The macroeconomic-level predictors were derived from 41 different indicators collected from 25 Mexican communities.

A growing dimension of migration modelling involves utilization of agent based techniques. Agents can be used to represent either individuals or households and are programmed to act on the stimuli they receive from the environment in which they live. In this way, agents influence and are influenced by the environment around them as well as other agents they encounter in a simulation. However, the complexity and data requirements of such models can be daunting. Using open source tools such as NetLogo can help strike a balance between complexity and abstraction. Spatially explicit, stylized agent based models have shown utility, particularly during preliminary stages of research in sharpening system conceptualization and evaluating alternative policy scenarios [27]. In a more detailed analysis of human cognition, Grothmann and Pratt [28] developed a socio-cognitive model of private proactive adaptation to climate change based on Protection Motivation Theory [29]. Cognition is divided into two key components, risk appraisal and adaptation appraisal, which only comes after the risk appraisal exceeds some specific threshold of threat. A limitation of this approach is that it deals with proactive behaviour, whereas migration is often a reactionary response. To overcome this issue, Kniveton and others [30] integrated the Theory of Planned Behaviour [31] into an agent based modelling approach. This theory proposes that the proximal cause of behaviour is 'behavioural intention', a conscious decision to engage in certain behaviour. Behavioural intention is modelled as the interaction of behavioural attitude, subjective norms and perceived behavioural control. The first element captures the agent's perception of the utility of taking a particular action (e.g., migration), while the subjective norm addresses the belief that a significant other thinks the agent should perform the behaviour. The perceived behavioural control is the adaptive capacity of the agent to follow through on an intended action.

DIFFUSION MODEL OF MIGRATION

Here a theoretical model of human migration is introduced that integrates key elements from past theoretical constructs. While the current framework is theoretical, the intent is to implement the model within a broader agent based modelling platform. The theoretical model combines aspects of the Protection Motivation Theory [29] and Theory of Planned Behaviour [31] within the mechanistic framework of Fick's first law of diffusion [32]. The goal is to provide an intuitive modelling formulation that accounts for both proactive and reactive response to changing environmental conditions (e.g., climate, economy, conflict). The Protection Motivation Theory contributes the *risk appraisal* and *adaption appraisal* building blocks of the model. The *adaptation appraisal* is further resolved using the Theory of Planned Behaviour which is organized according to three interacting elements; *behavioural attitudes*, *subjective norms* and *perceived behavioural control*. These behavioural elements are cast in a more instructive framework using the analogous mechanistic model of diffusion.

Diffusion Framework

Fick's first law of diffusion simply states that the total one-dimensional flux, J, is directly related to the gradient of the concentration, c

$$J = - A * D * dc/dx \tag{1}$$

where A is the cross-sectional area to diffusion, D is the diffusion coefficient for a solute diffusing in bulk fluid and dc/dx is the concentration gradient. Solutes diffuse from locations of higher concentration to lower concentration, while characteristics of the host fluid, as represented by the diffusion coefficient, modulate the rate at which diffusion occurs. The physical process of diffusion is directly analogous to Lee's simple model of migration. The push-pull is represented by the concentration gradient while the intervening physical and social impediments between the point of origin and destination are represented by the diffusion coefficient. Further, the cross-sectional area to diffusion is analogous to the cross-section of population who consider migration as a viable adaptive action.

According to the Theory of Planned Behaviour, *behavioural intension*, I, (see Figure 1) is informed by *behavioural attitudes*, BA, *subjective norms*, SN, and *perceived behavioural controls*, PBC

$$I = (BA * SN) * PBC \tag{2}$$

Perceived behavioural controls are simply the perception of whether or not one has the assets/experience necessary to undertake an intended action (i.e., adaptive capacity). This is analogous to the diffusion coefficient in Equation 1 and the impediments in Lee's conceptual migration model. *Behavioural attitudes* measure ones perceived betterment by taking an intended action, such as improved wages, living conditions, or personal security. *Subjective norms* address the influence of networked peer approval on an intended action. These factors together form a *migration potential*, MP, and thus a push-pull between the point of origin and destination. Recasting Equation 2 in the form of the diffusion equation (1)

$$I = - PBC * dMP/dx \tag{3}$$

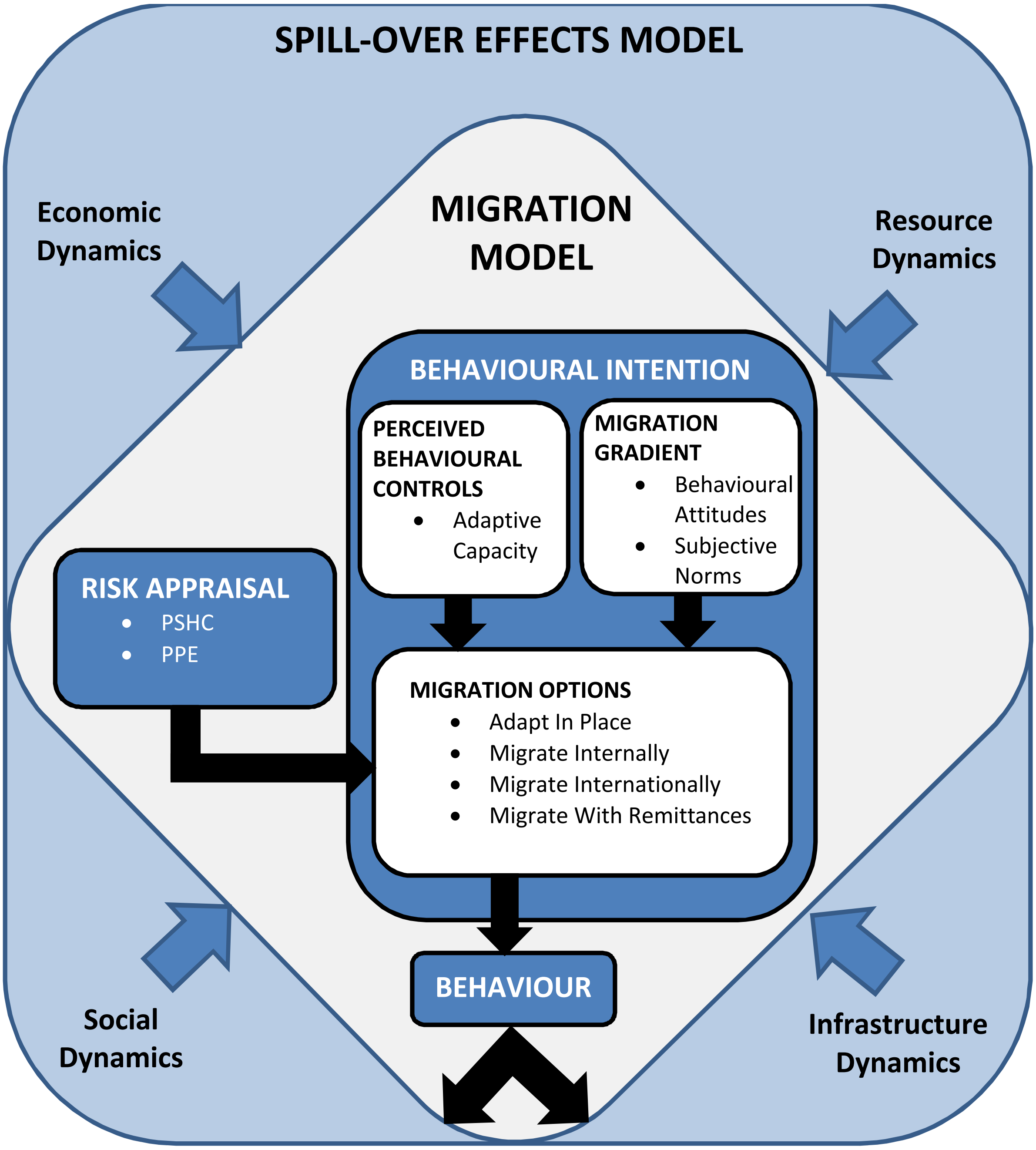

Figure 1. Schematic of diffusion model embedded in the spill-over effects model.

The spatial component, x, simply characterizes the distance between origin and destination. Others have considered the analogue between migration and diffusion; however, taking a very different approach [33].

Each agent in a given analysis is faced with the decision to choose between multiple adaptive actions. That is the agent could choose to adapt in place or migrate. Migration could involve an internal (rural-to-rural, rural-to-urban, urban-to-urban) or international move. The migration could involve a single family member or multiple members. Thus, a *behavioural intension* is scored for each agent and each option.

Migration Potential and Gradient

Migration potential is a measure of the state of human security at a given location. UNDP's Broad Spectrum of Human Security Indicators [34] provides a convenient list of representative measures. Seven broad security categories are listed including economic (wages, cost of living), food (caloric intake), health (infant mortality), environment (access to sanitation), personal (violent crime incidence, deaths due to conflict), community (migrant stocks in other countries) and political (corruption, disaster response). These measures span both the *behavioural attitudes* and *subjective norms* concepts foundational to the Theory of Planned Behaviour. While selection of specific *migration potential* measures will likely vary by problem and location, for a given simulation the set of measures must be consistent and referenced to a shared datum/baseline.

Migration is driven not by the absolute value of the *migration potential* but by the gradient. The gradient is calculated as the ratio of the difference in *migration potential*, *MP*, and the *distance*, *l*, between the point of origin and destination,

$$dMP_{i,j}/dx = (MP_j - MP_i)/l_{i,j} \quad (4)$$

where the subscript *i* designates the point of origin and *j* the destination. High *migration potential* values at the point of origin "push" migrants out while low *migration potential* values at a specific destination "pull" the migrant in. The gradient is further enhanced where the *distance* between origin and destination is small. In this way, migrants will be attracted to destinations in which the gradient is the lowest (most negative).

Perceived Behavioural Controls

Perceived behavioural controls are synonymous with the concept of adaptive capacity. Adaptive capacity is context-specific and varies from country to country, from community to community, among social groups and individuals, and over time. However, in general terms several past works can be utilized to help guide development of location/event specific adaptive capacity measures [35-37]. Such measures can be organized according to five broad categories:

1. Financial capital – one must have the financial resources to fund a given adaptive option or to wait out an impact (e.g., savings).
2. Human capital - health, education, experience are key factors in allowing an individual to diversify in times of trouble (e.g., find a new job, apply new farming practice, adjust to a new culture/language). These also promote innovation toward new and different personal solutions.
3. Social capital – the social network one has access to that will help them in times of trouble or group that can cooperate to accomplish changes that are beyond the reach of a single household.
4. Physical/built capital – access to infrastructure and technology may be an important determinant in some cases; specifically, improved roads to accelerate movement or internet access to learn about distant job opportunities.
5. Governance – policies, information dissemination, border controls, insurance, etc. are key factors in enabling and organizing adaptation action.

Perceived behavioural controls (Figure 1) or adaptive capacity effectively operates as a filter in the *behavioural intention* equation (Equation 3). That is, only the population that possesses the necessary adaptive capacity can realistically adopt the associated behavioural intent.

Risk Appraisal
Protection Motivation Theory [29] provides a quantitative basis for modelling the psychological steps toward action in response to a perceived change in an agent's environment. The associated analysis combines two elements, *risk appraisal* and *adaption appraisal*. The *adaption appraisal* process is synonymous to the *behavioural intension* (Equation 3) analysis of the Theory of Planned Behaviour. *Risk appraisal* defines the cross-section of population that would consider migration as a viable option. In this sense the *risk appraisal* is similar in concept to the cross-sectional area to diffusion in the diffusion model analogue.

According to the Protection Motivation Theory the *risk appraisal* is composed of two elements; *perceived probability of exposure, PPE,* and *perceived severity of harmful consequences, PSHC* (Figure 1)—consistent with the fundamental definition of risk:

$$RA = PPE * PSHC \tag{5}$$

PSHC can be quantified in terms of the state of human security at the point of origin, or effectively the *migration potential*. As *migration potential* increases, coping strategies are stressed and action is prompted. In this way, *PSHC* is quantified as the proportion of population that falls in each of three threshold groups, (1) that population with a low MP_i and thus no strong driving force to migrate; (2) that population that feels stress but can cope; and (3) that population with high MP_i and thus has been pushed beyond their coping capacity. *PPE* captures the personal choice aspect of the migration decision, depending on such factors as gender, age, community, skill level, and past migration experience. Note that where *category 3 PSHC* population is trapped (i.e., lack capacity to migrate) they form a population pool for criminal activity and/or political unrest.

Model Formulation
Ultimately the *migration rate, M,* is estimated by multiplying the *risk appraisal, RA* (Equation 5), by the *behavioural intent, I,* (Equation 2):

$$M_o = RA_o * I_o \tag{6}$$

where the subscript *o* distinguishes between the different migration options (e.g., local, international migration to country *j*). Substituting Equations 3, 4 and 5 into Equation 6 and reframing in a form consistent with Fick's first law of diffusion (Equation 1) yields

$$M_{o,g,s,j} = -PPE_{o,g,s,j} * PSHC_{o,g,s,j} * PBC_{o,g,s,j} * (MP_{o,g,s,j} - MP_{o,g,s,i})/l_{i,j} \tag{7}$$

The multiple subscripts reflect the fact that unique migration rates are evaluated by option, *o*, gender, *g*, skill level, *s*, and destination, *j*.

SPILL-OVER MODEL

The ultimate focus of this work is on the changing climate, its influence on resource provisioning and the resultant threat to human/national security. Migration and the accompanying spill-over effect are at the heart of the human/national security issue. Toward this end a tool is being developed to quantify the risk (intensity and frequency) of spill-over; specifically, 1) identify vulnerable regions, 2) quantify the emergent risks, 3) offer resilient solution options, and 4) provide usable and defensible information to policy makers. Given the inherent uncertainties and associated data limitations, analyses are formulated according to a risk based assessment framework for determining what pre-emptive adaptive measures are most necessary when and where.

A prototype spill-over model is nearing completion. The previously described migration model operates within the framework of the spill-over model. Specifically, the spill-over model simulates the environment in which agents consider the option of migration. The spill-over model supplies the cues that the agents consider as they weigh options on how to respond to changing environmental conditions. The spill-over model also considers the impact that the selected adaptive response has on the environment.

The prototype spill-over model is constructed in Vensim PLE Version 5.1[38]. Because of the project's concern for climate affects, the modelling approach assumes a 50-year time horizon. Agents in the current model are distinguished at the country level by country of residence, country of origin, gender, education/skill, age, and rural/urban roots. The model endogenously simulates economy, labour, population, disease, violence, resource, water, and food sectors (Figure 2). Key model dynamics include:

- Birth and death rates change as a function of education, location, disease, food, water, income and violence.
- All behaviors reflect institutional, tradition, and cultural differences among populations.
- Economic modeling includes gross regional product, wages, income, employment/unemployment, as a function of governance, technology, investments, land, resources, water, food, disease, and climate change.
- Food, water and resource availability includes simple supply and demand simulation that act as a placeholder to couple more sophisticated water and food simulations in the future.
- Climate effects include temperature, precipitation, and extreme event designations. Climate is assumed to be probabilistic and sampled from the CMIP5 data set [39].
- Migration and economic dynamics include the effect of remittances.
- Violence and migration dynamics are influenced by spill-over effects from other regions.

The prototype model is being developed to explore migration and spill-over for the developing nations in West Africa. Specifically, Mali serves as the focus of the analysis with migration considered within country, between rural and urban, as well as international migration between its neighbours as well as more distant migration to developed nations.

Formulation of the spill-over model for Mali also involves calibration of the endogenous migration model (Equation 7). Several data sources are being utilized to accomplish the calibration, including the "United Nation's Trends in International Migrant Stock: Migrants by Destination and Origin" database, which provides a historical measure of migrant's choice of destination given their country of origin [40]. Additional migration data including both internal and international migration (neighbouring countries) are available for the years 1988-1992 from The Network of Surveys on Migration and Urbanization in West Africa (NESMUWA) [41]. Indicator data characterizing environmental conditions (e.g., wages, infant mortality, work force, population) within the West African nations are taken from the World Bank's Africa Development Indicators database [42]. Calibration is required to determine the appropriate mix of indicator data and associated weighting to construct the *migration potential* and *perceived behavioural controls* metrics; to establish meaningful thresholds on the *perceived severity of* *harmful consequences* metric; and, define the *perceived probability of exposure* with respect to gender, skill-level, destination, and migration option.

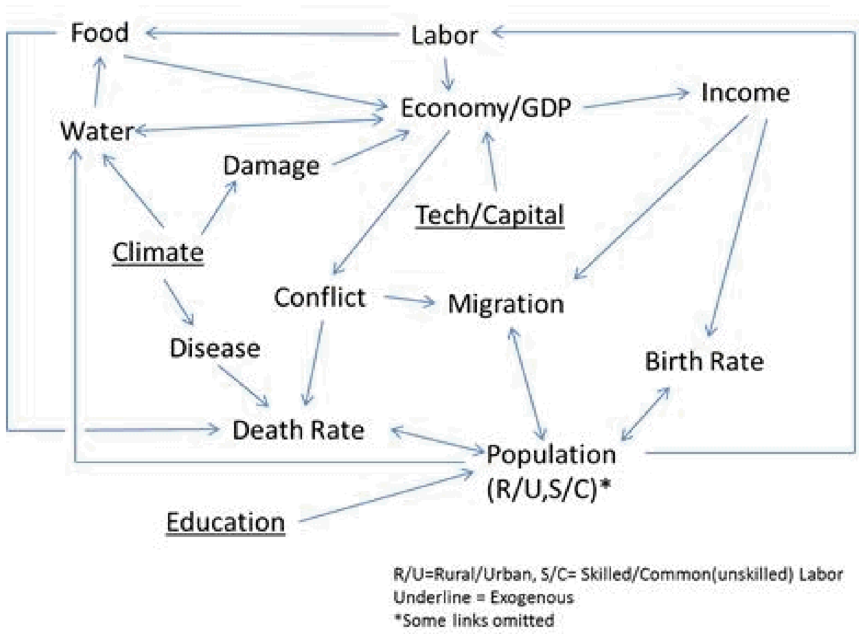

Figure 2. Overview of the basic spill-over model interactions and considerations.

CONCLUSIONS

Changing climate conditions will undoubtedly place increased stress on vulnerable populations, potentially encouraging greater internal and external migration. If not managed, migration directly impacts the receiving destination, while indirectly impacting international security through costly humanitarian aid, conflict, increased crime/terrorism, and international trade. We term this the spill-over effect. Currently there is a lack of quantitative tools to analyse this issue. Toward this need, system dynamics and agent based modelling are being integrated to create a framework to identify regions vulnerable to the spill-over effect and to explore potential mitigating and/or adaptive measures.

This paper focuses on the theoretical framework for the the migration modelling component of the broader spill-over model. Existing theory is reviewed and integrated in a unique manner to provide a new look at human migration. The migration model combines aspects of the Protection Motivation Theory and Theory of Planned Behaviour within the mechanistic framework of Fick's first law of diffusion. In this analogue migration moves in response to the relative difference in living conditions between the point of origin and destination (the *behavioural attitudes* and *subjective norms* of the Theory of Planned Behaviour), similar to the action of the concentration gradient in the diffusion model. Migration is modulated by *perceived behavioural controls* (Theory of Planned Behaviour) in a manner similar to the diffusion coefficient in the diffusion equation. Migration is further influenced by the cross-section of the population that considers migration as a viable adaptive option (*risk appraisal* of the Protection Motivation Theory); consistent with the cross-sectional area of diffusion that limits solute movement.

Here the migration modelling framework is established and explained. A prototype model is being developed to explore migration and spill-over for the developing nations in West Africa. Work is on-going to calibrate the model. Likewise, efforts to construct a beta version of the broader spill-over model are nearing completion.

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