Simulating the Food and Nutrition System in Rural Zimbabwe to Support Targeting of Emergency Aid

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Abstract. A simulation model of the food system for a district of Zimbabwe is described. The simulation database mimics the population of the study district as closely as possible, with one record for each of 40,000 households. The large number of micro simulations captures the temporal and spatial variability of malnutrition and disease that is observed in practice. The characteristics and resources of the simulated households are derived from census, agricultural and health statistics by applying field survey results. Each simulation processes all 40,000 household records in ten-day time steps, throughout an agricultural year. Localised rainfall is estimated from satellite and meteorological data, whilst other changes in environmental, economic and social conditions are sourced from secondary data. Household response to these changes is modelled from a rule base that takes account of location and season by including logistic regression analyses of field survey data, together with published agro-economic and epidemiological models. Changes in levels of grain, cash, other assets and disease initiate interactions with other households. Local imbalances of demand and supply are satisfied through traders who transfer grain across the district. Similarly, outbreaks of disease diffuse through the district by population movement and indirect infection vectors, such as insects. The paper discusses how micro scale activity propagates emergent behaviour in the food and nutrition system as a whole. Such simulations offer a generic tool that can be used early in the agricultural season to evaluate the full year outcomes from several rainfall, disease and food market scenarios. Villages and wards can be identified that will require food or medicines, rather than awaiting the onset of malnutrition and disease to trigger aid supplies. Future research will support multi year simulations, providing a tool for evaluating rural development projects and long term intervention policy.

1. INTRODUCTION

Food security in developing countries is now recognised as the result of a variety of economic, environmental and health factors, coupled with the complex social relationships within and between households and communities. Hay [1986] suggests that food availability, both in terms of quantity and quality, is mediated by a *hierarchy of relationships* – households within communities, communities within countries, countries within the world at large. Tomkins and Watson [1989] emphasise that the underlying cause of poor nutritional status is the interaction of disease and poor care with the effects of reduced food access at household level. Tomkins and Watson describe this as the *malnutrition-infection complex*. Thus, variability in the spatial and temporal levels of malnutrition requires an examination of the factors that influence food access and health at household level, rather than more limited analysis of supply side variables. Maxwell and Frankenburger [1992] observe that by the end of the 1980's the focus had shifted from national and global food supplies to questions of *access to food at household and individual levels*. The concept of household food security embraces four aspects: *sufficiency* of food in terms of quantity and quality for an active healthy life; *economic access* to food either by own production, purchase, exchange or gift; security, balancing vulnerability, risk and insurance; and *variability over time*.

Data collection techniques used in the study of food systems have also changed: questionnaire-based surveys, popular in the 1970s, are now supplemented by more qualitative data gathering. These newer techniques include interviews with 'key informants', anthropological studies, and participatory appraisal methods. A food systems model therefore needs to be capable of handling both 'hard' information from questionnaire surveys and 'soft' information from qualitative sources. Indeed, Maxwell [1996] suggests the need for a flexible, community-based approach to 'post-modern food security', where targeting and design of interventions reflect the diversity of coping strategies. Local information and local action in a decentralised, open system will be the future paradigm rather than the top-down, resource intensive relief programmes of recent years.

This paper describes the development of a model of the food and nutrition system for a district of Zimbabwe that uses local information, from a variety of sources, to simulate future patterns of nutritional insecurity. The model draws upon the analysis of a field survey, carried out in the Buhera District, to provide a rule base of household behaviour, supplemented by more qualitative information drawn from 'key informants' such as local health workers and agricultural extension staff. The variable response of communities and households to changing environmental conditions throughout an agricultural season results from the micro-scale stochastic processes underlying such behaviour.

The model predicts the levels of malnutrition for each ward of the district. The simulation of ward-level malnutrition rates offers several potential advantages over more conventional techniques based on aggregated secondary data. Tagwireyi and Greiner [1994] have suggested that the malnourished population in a given rural area of Zimbabwe comprises some individuals who are malnourished because of infection, some who are malnourished because of inadequate food access, and some who are malnourished because of problems related to parental care. By working from the individual level upwards, this model captures these multiple causes of malnutrition.

2 THE FOOD SYSTEM IN BUHERA: COMPLEX AND HIERARCHICAL

2.1 Zimbabwe's food security paradox

Until recently, Zimbabwe was regarded as being self-sufficient in food, with the national per caput calorie production exceeding WHO recommended daily requirements. White maize is the principal staple, with millets and sorghum being important drought resistant subsistence crops. Although aggregate national food supplies are adequate, significant levels of malnutrition exist, particularly in rural areas, with both inter and intra seasonal variability being evident [Ferro-Luzzi et al., 1992]. Jayne and Chisvo [1991] have dubbed this Zimbabwe's 'food security paradox'. The structure of agriculture in modern Zimbabwe reflects its colonial past. It now comprises four main sectors: a large scale commercial sector; a small-scale commercial sector; resettlement areas; and the Communal Lands. In the Communal Lands, the majority of farming households are grain-deficit in most years [Corbett, 1994; Vaze et al., 1996]. In many of these households, one or more of the adult males will work in the cities or further afield for part of the year. Income is remitted to the household periodically to supplement subsistence food production by purchased staples from local market sources. Since independence, the government has made substantial enhancements to the infrastructure in the poorer rural areas by improving agricultural extension services, roads, transport, water/sanitation and healthcare. These changes have been reflected in better mortality and morbidity statistics; nonetheless, malnutrition rates remain high, particularly in the semi-arid and arid lands to the south and west of the country.

2.2 Research project in Buhera District

Research was carried out in the Buhera District of the Manicaland Province, Zimbabwe. It is approximately 8,000 sq. km in extent, with a population of 204,000 people in about 40,000 households [CSO, 1994]. Administratively, it comprises 36 wards, usually split into 6 or 7 village development committees of about 160 households each. Agricultural potential [Surveyor General, 1984] varies between semi-intensive (zone III: 650 - 800 mm rainfall) in the north of the district and extensive (zone V: less than 450 mm rainfall) in the south.

Data collection comprised a household survey and the extraction of numerous secondary datasets. In the former, 354 households were surveyed over twelve visits during 1994/95. Details of demography, income, agricultural activities, food sales/purchases and consumption patterns, water/sanitation, education, health, use of healthcare were collected [Gundry et al., 1997]. Adults and children were anthropometrically surveyed to assess seasonal changes in body mass and height. Secondary data collection comprised ward and district level data covering administrative boundaries, environmental variables (rainfall, temperature), natural resources (forests, rivers, lakes, terrain), infrastructure (roads, transport availability, markets, potable water supplies) and health statistics (morbidity, mortality, growth monitoring data, healthcare availability). A specially prepared sub-ward analysis of the 1992 Census was provided to enhance the published Central Statistical Office reports.

2.3 Hierarchical models of complex systems

It is suggested that the operation of the food and health system in Buhera (and similar districts of developing countries) can be described as a 'complex system'. In such a system, outcomes at the macro-level cannot be understood by examination of the system from a single perspective or predicted by the implementation of deterministic models applied to aggregate, homogeneous data describing the individual agents which operate within the system. Rather, the patterns of malnutrition that emerge are the result of the micro-scale processes and the stochastic nature of the interaction of the agents operating at the various hierarchical levels across the district. By representing this hierarchical structure in a layered model, such emergent behaviour can be replicated and readily obtainable data may more easily fit the framework.

It appears that many researchers are considering the explicit recognition of hierarchies within their models and several ideas have been proposed for programming such structures. Advances in the applications of cellular automata (CA) [Wuensche and Lesser, 1992] have enabled researchers to model evolutionary development over extended time scales, by implementing simple deterministic rules for the interaction of adjacent cells. With object oriented programming methods (OOP) [Booch, 1991] and more powerful computer processors, multi-layered simulations have become a feasible approach to the creation of hierarchical dynamic models of large systems. Gilbert and Conte [1995] report various models of social interaction, using CA and OOP, to simulate and analyse contemporary societies and support the archaeological assessment of past community structures. Langton [1995] at the Santa Fe Institute labels the subjects of such models as 'complex systems'. Casti [1996] observes that 'such bottom-up models rely on our knowledge of the agents and their interactions with each other, which then generate a pattern at a higher level than the agents themselves' (p 7). In the early stages of this research, the application of systems dynamic modelling methodologies [see Hannan and Ruth, 1992] was also explored. Its attractions were the ability to view the food system in a holistic way, capturing the key linkages between the various influencing factors and its explicit treatment of time. However, the limited capabilities of proprietary software effectively restricted the model to dealing with aggregate populations rather than individual households and communities. Use of qualitative data was also restricted. The approach finally adopted – simulation model coupled to expert system – captures the essence of the hierarchical system, but allows for individual variability by applying probabilistic and deterministic rules to the households and communities within the structure so creating a complex system model. It takes explicit account of temporal and spatial variability.

3 A SIMULATION MODEL OF THE FOOD SYSTEM

3.1 Overview

The structure of the simulation model is shown in figure 1. The core of the model is shown in bold and comprises a *simulation engine*, which applies stochastic and deterministic behavioural rules from a *rule base*, to the *population database*, over a number of time steps t_0 through t_n. For each time step, *short-term factors*, particularly changes in rainfall and disease rates, are applied to each ward and the resultant response of households to these changes is propagated to the higher-level community structures of village, ward and district. Each time step t_x, represents a ten day period (dekad), since this is the standard unit for rainfall mapping from satellite imagery. At time t_n, the end of the agricultural season, the *output module* produces a series of tables, maps and statistical data is provided to the user.

Five subsidiary modules are associated with the core: pre-processing of secondary data; analyses of field survey data; data generation of the population database and the short-term factors; and, user modification of the rule base.

3.2 Simulation engine

The simulation engine maintains overall control of the temporal, hierarchical and spatial processing cycles. For each time step, the individual data records representing household members from each household, within each village, are processed against the infection, care and recovery rules to establish the levels of illness within each household arising from the changed disease rates. Illness is then combined with the individuals' food access to establish whether the necessary conditions exist to produce malnourishment in the household, in addition to illness. Where a household member is suffering from malnourishment or illness, the impact upon the household will be that the ability to work on the land, in employment or around the home (including care of children) will be reduced and this will effect other variables, particularly income. After processing individual household members' records for the whole database, the processing then moves up the hierarchy to simulate household responses. At the household level, the principal behavioural processing will be concerned with the changes in food stocks through harvest, consumption and purchases, sales and gifts. Such changes interact with changes in household cash and other assets, including livestock. Of particular note is the triggering of sale and purchase transactions for grain and other staples, which will then be pooled in the next level up the hierarchical processing, the village, to establish whether a community is in net food surplus or deficit. Where communities show surpluses or deficits, these will be transferred to other communities requiring or having food, through agents, representing the market mechanisms that exist within the district at ward and higher levels. Similarly, a healthcare uptake model enables attendance at health centres to be simulated over time from the levels of household illness within the clinic catchments. Once processing has been completed for every hierarchical level, for every ward of the district, the simulation engine will increment the temporal control by one time step and the hierarchical and spatial processing will be repeated.

3.3 Rule base

The methodology for the derivation of the rule base comprises statistical analyses of the primary and secondary data and is comprehensively described for patterns of infection and recovery at household level in the accompanying paper by Wright et al. [1997a]. The derived rules can be either stochastic or deterministic, as suggested by the underlying data analyses. The rule base has been encoded in proprietary expert system software to facilitate ease of user understanding, modification and consistency of application.

3.4 Population database

The population database has been extrapolated from the 1992 Census for Buhera District. Ideally, the 'real' household data would be available for constructing this database. However, because of requirements for strict confidentiality, the Government of Zimbabwe's Central Statistical Office provided, as a special exercise, a summary of the household data at sub-ward level. From these summary records, a database of households has been created to mimic, as far as possible, the underlying 'real' records.

It should be noted that this extrapolation is a potential source of modelling error as data generation of mimic records may fail to implicitly recognise the correlation of attributes of households and their members. Some attempt has been made to reduce this error by statistical analyses of the sub-ward summaries, but these comprise only about 200 records. Thus, correlations that would exist in the underlying households may be masked, as they are not statistically significant in the smaller sample size of the summary records. This analysis will be augmented by cross-tabulations of the attributes in the field survey sample. Furthermore, some key household attributes are not captured in the census and these will be estimated from the field survey sample using a similar method.

In addition to the household records, the population database will also contain records for higher level community structures: villages, wards and the district as a whole. It will also include records for economic agents: traders, markets and the Grain Marketing Board (GMB) and health care facilities: outreach centres, clinics and hospitals.

3.5 Short term factors

The rule base will be applied to the attributes of the various entities comprising the population database. Some of these attributes will remain constant for the simulated agricultural year e.g. type of sanitation, whilst others will alter dynamically e.g. food stocks. The changes in these dynamic attributes will occur as a result of changes in the short-term factors that influence the state or quantity of the given attribute. The short-term factors are principally rainfall, temperature, disease rates and economic variables, such as market prices of the principal staples. Rainfall will be derived from historic satellite data, which is available in ten-day intervals for areas of 50 sq. km. These historic data will be used to create rainfall scenarios, using the data generator, which can be used to invoke particular conditions appropriate to the simulation desired e.g. 'average rains', 'drought', 'severe drought'. Similarly, disease data will be derived from historic morbidity statistics to provide disease scenarios for the major disease groups.

3.6 Output module

The output module will provide users with various reports about the simulation, utilising geographical information system techniques as the central provision of output data. It will be necessary to evaluate with users which reporting methods are preferred. Clearly it is infeasible to display 40,000 household records. There are various choices of method: cartographic/graphical display of aggregated results, descriptive statistics or graphical display of a sample of individuals. Furthermore, users may prefer to see some averaged measure of multiple sample runs with the same scenarios started with different random seeds. They may also wish to review dynamic changes in the population database records, rather than simply seeing the year-end result. User workshops are planned for early 1998 in Zimbabwe and Europe to evaluate the most appropriate tools of user reporting for inclusion in the final version of the simulation model.

3.7 Calibration and validation of model

Calibration and validation of models that predict levels of malnutrition is difficult due to the absence of independent, comprehensive data covering the whole population under study. Standard government information is collected for partial populations only.

In Zimbabwe, child malnutrition statistics are available only for under 5's who have attended growth monitoring clinics; morbidity statistics are based on patients attending health clinics; and, agricultural statistics may omit some farmers e.g. dip tank censuses of livestock. The bias in these nationally available data presents problems for their use in calibrating models such as is developed herein. In an accompanying paper, Wright et al.[1997b] discuss various approaches to correcting the bias in such data for use in calibration and validation.

4 DISCUSSION: USE OF MODEL FOR TARGETING

4.1 Emergency food aid

The simulation under development considers changes in the food system over one agricultural year. As such, it will offer a decision support tool to government, aid planners and NGO's to evaluate at an early point in a season the likely outcomes from various scenarios of rainfall, disease, changing economic conditions etc. These outcomes will show the location and timing of likely nutritional insecurity and will be able to provide explanation of the underlying causes. With this information, planners should be able to locate trouble spots in advance, estimate the time at which aid is required and assess the most appropriate aid i.e. food, medicines or other supplies.

4.2 Rural development policy evaluation

If the simulation model performs satisfactorily over single agricultural years, it will be possible to develop a multi-year system that will enable the longer-term policy issues to be evaluated. Such multi-year simulations will present particular problems as they will need to incorporate explicitly the demographic changes that will occur. Note that the single year model will assume a steady state population for the district, although seasonal migration to cities for employment will be included.

4.3 Decision support *not* problem solution

Especially in developing countries, tools such as described herein are often thought to be panacea. As such, they are sometimes used uncritically and fail to achieve useful application in the longer term. The authors wish to stress that the simulation model described is not intended to be all encompassing and the rules incorporated for household behaviour are likely to require evolutionary development as experience of the model is gained. Substantial user input and local, indigenous knowledge are essential components. However, it is felt that even in the early period of use, where deficiencies in such models will certainly exist, benefit can accrue from their use by prompting planners and analysts to consider the impacts of their decisions from a systems standpoint, rather than viewing each aspect in isolation. In essence, the very act of using the model, even with its deficiencies, provokes critical appraisal of decisions and actions being made and stresses the linkages that exist between the various factors influencing food security.

5 CONCLUSION

This paper has presented a simulation model for the food system in a district of Zimbabwe that predicts the changes in nutritional status of the population within one agricultural year. It uses a simulation engine to apply a rule base (using proprietary expert system software) to a population database to dynamically model household behaviour in response to short term changes in environmental and other conditions. During each time step of one dekad, changes in households are propagated upwards in the social hierarchy, changing attributes of communities at village, ward and district level.

The advantages of such a modelling approach are:

- *Flexibility* – the model can be adapted easily by different users, who can modify the existing rule base or 'plug in' a new version based on other experts or field surveys. It can also be adapted for use in other locations, by 'plugging in' a different population database. Rewriting of substantial computer programs is not required.

- *Data availability* – using an expert system as the rule base enables both quantitative and qualitative data to be used in modelling household behaviour. This is of particular benefit in developing countries where data sets are often fragmentary or extensive use has been made of rapid appraisal techniques, using key informants.

- *Hierarchical* – the model adopts a 'bottom-up' approach by simulating the behaviour of households and the communities in which they reside with 'micro-world' stochastic and deterministic modelling. By modelling the complexity of the system in this way, patterns of malnutrition at community level may emerge which are not apparent using macro-level modelling techniques.

Some authors [David et al., 1993] are suggesting that 'second generation expert systems' include those using multiple methods, models and sources of knowledge. This simulation model fulfils those criteria. More importantly to these authors, the application of such technology offers an opportunity to provide advanced software tools to an area of need in developing countries which will supplement the limited human and information resources available. If the technique can be developed to provide a generic tool for aid planning and rural development support, better use can be made of the increasingly tight aid budgets being set by donors world-wide.

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