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A conceptual model to guide exploration of global food-water security

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Abstract: While food security can be approached as a local issue, it is strongly influenced by factors at inter-regional and global scales related to production, transaction (e.g. trade and distribution) and consumption, and by drivers such as climate, population growth, diet change, as well as social, political and technological developments. Action on food security therefore benefits from being informed by current global patterns and potential future changes and taking an integrated approach to assessing impacts of proposed responses. Modelling can notably contribute by assessing the influence of various factors on food security. Due to the significant complexity and uncertainty involved, model development and use is simplified by approaching it as an exploratory process rather than aiming for a comprehensive historically accurate model. We present a macro-scale conceptual model to help structure and guide this exploration. We begin with the broad question "Will future developments achieve and maintain food security?" with the intent of exploring alternate possibilities of future developments, definitions of food security and factors influencing this question, beginning with assessing whether there is enough green and blue water to meet dietary energy requirements under typical current and future climatic variation. The conceptual model guides the selection of factors to explore sequentially through modelling (keeping other variables constant), iteratively building complexity as necessary. This helps to construct understanding using manageable building blocks, with the conceptual model evolving as it is used. The staged decomposition of this complex issue provides a framework to help build capacity for individuals and government agencies to understand their actions and policy respectively in a global context, with the hope that improving knowledge of adaptation options can help secure food supply to everyone.

***Keywords**: food security, exploratory modelling, uncertainty*

1 INTRODUCTION

Food security is a key issue having both global and local implications, requiring an integrated understanding across sectors and spatial and temporal scales. The African Union notably announced 2014 as the year of Agriculture and Food Security in Africa to promote learning and dialogue on this topic.

This paper aims to contribute by providing guidance on exploratory modelling of food security. Modelling can support dialogue by assessing the influence of various factors on food security, but is subject to significant uncertainty in the face of the complexity of the issue and many unknowns about both the future and the current state of the system. While a comprehensive historically accurate model can help to understand past events, predictions into the future involve new unknowns that cannot be precisely evaluated (Rosenzweig *et al.*, 2013). To fill this gap, exploratory modelling can help plan for the future by exploring implications of varying assumptions and hypotheses (Bankes, 1993; Bankes *et al.*, 2001; Lempert *et al.*, 2003).

In this paper we present a conceptual model of food security, providing a big picture understanding, which draws on a number of existing paradigms for modelling food security. This is followed by the presentation of a potential exploration process involving a sequence of questions to answer using modelling. We finish with a discussion of the importance of a structured exploration approach and implications for food security. Note that our approach to food security emphasises water as a key food production input. This also fits with the Panta Rhei Research Initiative (Montanari *et al.*, 2013) of the

International Association of Hydrological Sciences (IAHS), focussed on improve ability of hydrology as a science to deal with changing biophysical and social context.

2 LITERATURE REVIEW AND CONCEPTUAL MODEL

Figure 1 shows a conceptual model of food security, not intended to be directly implemented, but used to help structure our understanding of issues in food security. It is represented as an influence diagram, with the broad question "Will future developments achieve and maintain food security?" interpreted in a personal form at the bottom of the diagram as "Do I have food security?" to emphasise the need to account for individual variation even in a global analysis. This makes room for everyday experience within scientific discourse, consistent with the intention that the conceptual model be broadly inclusive.

This conceptual model draws on a variety of existing models. The main chain of influences down the centre of the diagram roughly corresponds to a supply-demand chain, with supply of water to agriculture and food transported to the consumer. Other physical inputs to food production, transaction (e.g. trade and distribution) and consumption are identified along the way. This corresponds to analysis of material flows, as used for example in Sankey diagrams in the context of the food-energy-water nexus (Curmi et al., 2013), or physical input-output models of the economy, which have been used to develop food supply scenarios (Larsen *et al.*, 2011).

In order to focus on water supply and demand, we then split the main chain at the provision of crop-available water, marked in red. Later in this paper, we will specifically build on this approach, which has been used to evaluate food security by comparing supply of water for agricultural production to demand of water (Rost *et al.*, 2008; Gerten *et al.*, 2011; Kummu *et al.*, 2014).

A number of influences feeding into the chain (in orange) are related to the monetary rather than physical economy. Food security depends on ability to pay for labour, technology, agricultural inputs, transport and access to land and water. It also depends on how food and resources are allocated by existing market mechanisms. This links with economic models including hydro-economic modelling (Qureshi et al., 2013) and general equilibrium theory (Arrow and Debreu, 1954), which identifies prices and quantities of goods resulting in equilibrium with several interacting markets allowing evaluation of effect of price or production shocks or food aid (e.g. Adelman and Berck, 1990; Gelan, 2006).

The conceptual model however recognises a need to go beyond physical and economic concepts. The tail end of the main chain corresponds to the commonly used conceptual model of food security in terms of food availability, access (sufficient resources to obtain appropriate foods), and utilisation (appropriate use based on knowledge of basic nutrition) (FAO, 2012; Porkka *et al.*, 2013). The fourth dimension of food security, 'stability', is implicit in the reference to change and variation in climate, population, and political stability. We also include notions of composition of diet (Edwards et al., 2011), impact on ecosystem services, need for human capital, and potential interactions with personal safety, political instability and the impact of disease on nutrition. Note that if we had the space to unpack these concepts further, the impact of water would also be seen, for example, in disruption of access to food by flooding and use of contaminated water in food utilisation or processing.

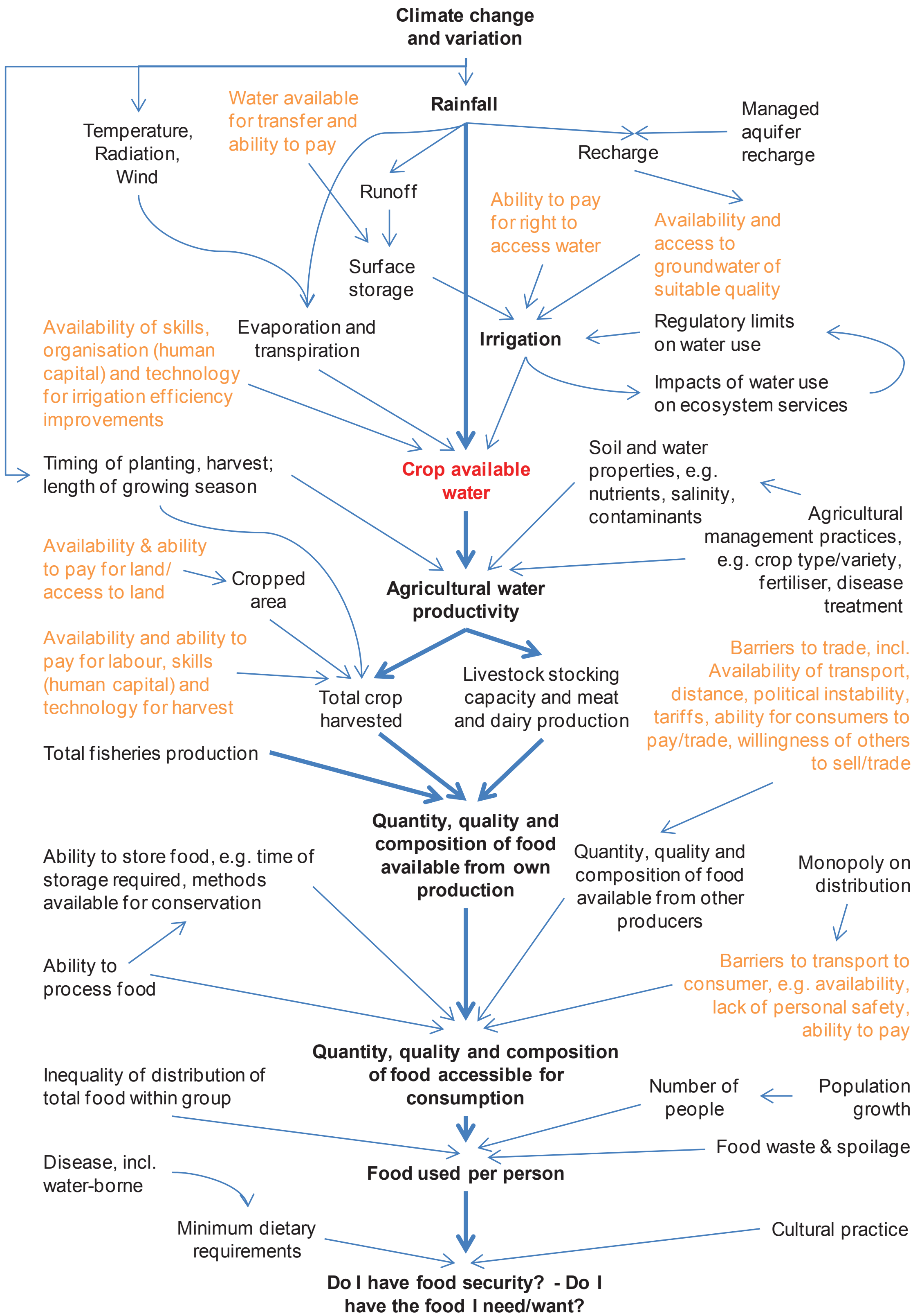

Figure 1 Influence diagram showing conceptual model of issues determining food security. The main chain of influence is centred and in bold. Issues related to monetary economy are in orange. 'Crop available water,' the primary focus of this paper, is marked in red.

3 POTENTIAL PROCESS TO EXPLORE FOOD SECURITY

The conceptual model presented above needs to be accompanied by some process to navigate it. The conceptual model provides a big picture that helps understand how factors fit together and influence each other. It is not possible for any single model to adequately address all the issues captured. Instead, we take the perspective that modelling will necessarily involve creating a number of different *model instances*, defined as $F_i(\boldsymbol{\theta}_i, \boldsymbol{x}_i)$, $i \in \mathbb{R}$, composed of different model structures F_i, sets of parameter values $\boldsymbol{\theta}_i$, and inputs or boundary conditions $\boldsymbol{x}_i$. There is therefore a need to critically select what aspects of the food security issue are included in any given model instance. So the conceptual model's role is to help understand what is left out rather than dictating what should be included. This helps to identify limitations that can be followed by other model instances. This results in an exploration process, the broad structure of which can be mapped out ahead of time to provide some direction, much as a hitchhiker chooses a road to stand on even if they do not know each car's destination.

Table 1 summarises one such exploration process as a sequence of questions to be answered using modelling. Each broad research question has been translated using (examples of) corresponding hypotheses that would be tested using results from various model instances, expressed as closed questions, with pre-determined answers (Guillaume and Jakeman, 2012). The exploration process is described in greater detail in the rest of this section. To provide some context, the fundamental principles influencing the design of this process of exploration are:

- Consider model instances that provide highest return for effort first
- Build on what is already known, but bear in mind how it fits with the bigger picture conceptual model. Sometimes new questions can be answered just by reinterpreting existing results, but eventually it may be necessary to also alter model inputs, parameters and even modelling paradigm (Kelly et al., 2013)
- More than one plan for exploration may be suitable, do not aim to find a 'best' plan
- Exploration of complex issues can never be complete. We accept that both issues present in and missing from the conceptual model may be omitted from a plan for a given project.
- Always relate global context back to local, and therefore high-level international ambitions to practical on-the-ground implementation.

The broad question "Will future developments achieve and maintain food security?" is first approached with an initial analysis (Kummu et al., 2014) that compares water availability and requirements for each food production unit (FPU) for each year, as summarised in Table 2. FPUs are sub-regions that correspond to a hybrid of river basins and economic regions. Food demand (as water required) is calculated as population * hunger alleviation dietary requirement (kCal/capita) * (1 – food waste ratio) * agricultural water productivity (m3 water/kCal food). Food supply (as water consumed by crops) is calculated as sum of green water and blue water. Green water is crop evapotranspiration under rainfed conditions. Blue water is additional evapotranspiration with irrigation. The cropped area and irrigated area are fixed.

We take a local approach and focus on a single FPU. Applying the analysis to all FPUs then allows the grouping of locations with shared concerns and options for future development. We evaluate the FPU's food sufficiency for each year, i.e. whether water consumed by crops is greater than or equal to water needed to satisfy dietary requirements. If it is not, we consider whether storing food across years (as virtual water) would be sufficient. Initially, this is evaluated by verifying whether there is a deficit when averaging food (water) supply and demand across a 30-year period.

If storage is not sufficient, we consider the potential for trade (Porkka et al., 2013) by considering the food surplus/deficit in other FPUs, expressed as virtual water (Allan, 1998). If the country in which it is located is self-sufficient, then domestic trade may provide security in deficit years. Continuing to larger scales, it may be similarly necessary to import food from within the region or outside the region. This analysis crucially shows the level of dependence on trade.

Table 1 Sequence of questions in exploration process to tackle "Will future developments achieve and maintain food security?"

Research questions	Corresponding hypotheses
• What level of trade or storage is needed to achieve food security in the FPU (at the level of hunger alleviation)?	• Is food security already achieved? • Does storage achieve food security? • Does domestic trade? • Does regional trade? • Does inter-regional trade?
• Under what alternate scenarios of interest is this result altered?	• e.g. does a different climate period require the same level of trade or storage to achieve food security?
• Under what scenarios would the FPU transition to being independent of trade, i.e. achieve food sovereignty (at the level of hunger alleviation)?	• e.g. Is it possible to attain the irrigation efficiency that would achieve food sovereignty? • e.g. Is it possible to attain any of the combinations of cropped area and waste ratios that would achieve food sovereignty?
• What points of failure could affect the transition to food sovereignty?	• e.g. If a drier climate eventuates, would it still be possible to attain food sovereignty though increased yield? • e.g. if the full volume of water required cannot be accessed, would it still be possible to attain food sovereignty?
• What side-effects could transition to food sovereignty have?	• e.g. With the level of irrigation required to meet total dietary water requirements, could any ecosystem services compromised? • e.g. if food and resources are allocated by (a CGE representation of) a market, does allocation of food between consumers meet total dietary water requirements?
• Which of the possible solutions for transition is more economically efficient?	• e.g. Does increasing cropped area result in the highest economic value relative to other options?

Table 2 Approach to determining whether food supply meets demand

Food supply (as water consumed by crops)	Food demand (as water required)
• Green water = cropped area * evapotranspiration when rainfed • Blue water = cropped area * *additional* evapotranspiration with irrigation • Food stored from previous years (as virtual water) • Food imported domestically (as virtual water) • Food imported within region (as virtual water) • Food imported from outside region (as virtual water)	Population * hunger alleviation dietary requirement (kCal/capita) * (1-food waste ratio) * agricultural water productivity (m3/kCal)

Each of these analyses required no additional model instances. We now turn our attention to how the initial analysis can be modified to explore the factors in the conceptual model. We start with key inputs and parameters of the initial analysis: climate, area under irrigation, cropped area, population, agricultural water productivity (m3/kCal), hunger alleviation dietary requirement (kCal/capita) and food waste ratio.

In each case, two strategies are employed. Firstly, any alternate scenarios of interest are run. For example, alternate climate period, climate change scenarios, projections of land use and population change, improvements in agricultural management practices improving water productivity, changes to a more water efficient diet and food waste reduction targets. In each case, we evaluate the impacts on potential food production and demand within a FPU in question, and assess whether the dependence on trade and storage is altered.

Secondly, we seek to identify transition points of interest by manipulating scalar variables (parameterising variables where necessary, e.g. using multipliers for climate change). Concentrating on the one FPU, we seek to identify the values (and combinations of values) of each variable that would lead to the FPU no longer being dependent on trade to reach the hunger alleviation dietary requirements. The scenarios generated in this way are used to prompt discussion of whether and how these outcomes could be achieved.

The analysis has now identified circumstances under which food self-sufficiency (or 'sovereignty') can be theoretically achieved. The results may however be dependent on a number of other parameters determining the calculation of the agricultural water productivity and area under irrigation in particular. With reference to the conceptual model (Figure 1), productivity is influenced by agricultural management including crop varieties, fertiliser, disease treatment, timing and length of the growing season, soil and properties including salinity and nutrients. We aim to test whether these factors could in fact impede achievement of food self-sufficiency. Starting from a best case scenario of each factor, we gradually relax assumptions by identifying conditions in which the current best case of each factor would fail to be achieved. The same principle is applied to other variables. The conceptual model indicates that increasing crop-available water through irrigation would depend on skills, organisation and technology, ability to pay for right to access water, storage of water, evaporation losses from water storage, potential for water transfers etc. This results in a sequence of possible points of potential failure that need to be addressed.

Although the analysis has argued that the solutions discussed can robustly achieve food self-sufficiency, it has not addressed whether the solutions may have undesirable side effects. Nor has it assessed the relative efficiency of each solution. We start by considering alternate uses of water. The conceptual model notes the potential for impacts on ecosystem services, which may lead to regulatory limits on water use being imposed at a later date. Expansion or intensification of agriculture also interacts with land, capital and labour. To address the relationship of food production with other sectors, the exploration process can move beyond the water supply/demand model to a computable general equilibrium (CGE) model. This allows the consideration of economic consequences of each arrangement. As the conceptual model indicates, food security may be dependent on ability to pay for water or the right to access water, land or right to access land, labour and technology, transport to consumer, transport for importation, and the ability of consumers to pay for these costs when they are passed on. The CGE therefore allows exploration of distribution of food and resources according to various assumptions about the local market economy. Just as with the initial analysis, while we may start with any existing CGE models, we then proceed to investigate possible means of addressing problems arising, possible transition points, and possible failure points that might prevent achieving them.

4 DISCUSSION AND CONCLUSION

In principle, a structured exploration approach, as described in this paper, has a number of distinguishing features relative to other modelling techniques. It facilitates learning from the differences between structures, parameters and inputs of model instances, but not in the same way as model inter-comparison (Rosenzweig *et al.*, 2013). It is intended to be suitable for a small group of analysts and even a single project. It tends to make easily-understood small changes at a time focussed on a particular question, such as by including an additional process or flow-on effect, rather than comparing whole model instances that may differ in many aspects. Whereas validation of an authoritative model in principle requires all uncertainties to be simultaneously addressed, exploration with a series of questions allows uncertainties to be addressed progressively, which is therefore more manageable. By avoiding the need for a single comprehensive model, exploratory modelling can also work with several simpler models that are easier to understand, dissect and discuss. By minimising the sunk costs inherent in large 'validated' models, it also becomes easier to revisit fundamental assumptions underlying the analysis. Relative to other exploratory modelling approaches based on computational analysis of large numbers of scenarios (Bryant and Lempert, 2010), the sequential question-based approach (Bankes, 1993) used here also allows a greater role for expert opinion, emphasising the need for development of theory. Note that the specific exploration process described here has not (yet) been undertaken, and whether theoretical benefits are achieved would depend on how it is executed.

From the point of view of food security, the proposed exploration process has the advantage of starting at the simplest stage of availability of water resources, and making use of existing strengths. It allows for transitions to more complex issues to be made gradually, producing lessons along the way, e.g. regarding patterns of water availability, importance of trade. Even if models are not 'validated', they can already produce important knowledge about how food security can be improved.

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