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# A food systems approach to researching food security and its interactions with global environmental change

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**Abstract** There is growing concern that satisfying societal demand for food over coming decades will be increasingly challenging. Much of the debate centres on increasing food production which has always been–and remains–an important strategy to alleviate food insecurity. However, despite the fact that more than enough food is currently produced *per capita* to adequately feed the global population, about 925 million people remained food insecure in 2010. Meeting future demand will be further complicated by deleterious changes in climate and other environmental factors (collectively termed 'global environmental change', GEC). This paper lays out a case for a food systems approach to research the complex food security/GEC arena and provides a number of examples of how this can help. These include (i) providing a framework for structuring dialogues aimed at enhancing food security and identifying the range of actors and other interested parties who should be involved; (ii) integrating analyses of the full set of food system activities (i.e. producing, storing, processing, packaging, trading and consuming food) with those of the food security outcomes i.e. stability of food access, utilisation and availability, and all their nine elements (rather than only food production); (iii) helping to both assess the impacts of GEC on food systems and identify feedbacks to the earth system from food system activities; (iv) helping to identify intervention points for enhancing food security and analysing synergies and trade-offs between food security, ecosystem services and social welfare outcomes of different adaptation pathways; and (v) highlighting where new research is needed.

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## Food security—a re-emerged topic

> "The world now produces enough food to feed its population. The problem is not simply technical. It is a political and social problem. It is a problem of access to food supplies, of distribution, and of entitlement. Above all it is a problem of political will." Boutros Boutros-Ghali, Conference on Overcoming Global Hunger, Washington DC, 30 November 1993 (quoted in Shaw 2007).

Food security (or more correctly, food insecurity) has long been associated with 'developing world' issues. From the perspective of the industrialised world, it has hence been the purview of development agencies (e.g. AusAID 2004; U.S. Government 2010), rather than government departments and other national agencies concerned with domestic agendas. In the UK, for instance, few–if any–government documents since the Second World War about conditions *within* the UK included 'food security' in the title. Recently, however, and largely driven by the food price 'spike' in 2007–2008, the notion of food security has rapidly ascended policy, societal and science agendas in countries worldwide, and has been the topic of special issues of leading scientific journals e.g. *Philosophical Transactions of the Royal Society B* (Godfray et al. 2010a) and *Science* (Science 2010), government reports (e.g. Defra 2006; EU 2011; Foresight 2011) and leading

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high-circulation media such as the *Economist* (21 November 2009; 24 February 2011). While most attention is directed towards the plight of many in the developing world, it is important to note that food insecurity occurs in all countries to some extent: in the US, for instance, the problem affects nearly 13 million households annually (Wisconsin WIC Program 2007).

Much of the food security debate understandably centres on aspects of food production and this has long been the subject of major research investment. Increasing production has always been an important strategy to help alleviate food insecurity, and it still is today. There is hence still a strong sentiment that producing more food will satisfy society's needs, and theoretically this is of course the case: produce enough and all will be fed. However, despite the fact that more than enough food is currently produced *per capita* to adequately feed the global population, about 925 million people remained food insecure in 2010 (FAO 2010). For many, this gap in production vs. need is more related to the political economy of interventions and political inertia in funding decisions than to technical ignorance (see quotation above). Given that food prices are again high (in March 2011, the food index remained 36% above its level a year earlier, World Bank 2011) there is a strong likelihood that this number will again rise.

This link between food prices and numbers of food-insecure people underscores the importance of the affordability of food in relation to food security. This is reflected in the commonly-used definition stemming from the 1996 World Food Summit (FAO 1996) which states that food security is met when "*all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life*". This definition puts the notion of access to food centre stage. Further, not only does it bring in a wide range of issues related to a fuller understanding of food security, but some key words such as "food production" and "agriculture"–which might have been expected in such a definition–are *not* included; the emphasis changed from increasing food production to increasing *access* to food for all. This definition also integrates notions of food availability and food utilisation. Many other definitions of food security exist; even by 1992 Maxwell and Smith had counted over 200 (Spring 2009) and more are still being formulated (Defra 2006). The majority of the more recent (i.e. since the 1990s) definitions have the notion of access to food central and are now manifestly very valuable in raising the profile of access to food *vis à vis* producing food.

While it is important to note that an inability to access food is the main cause of food insecurity in general, some parts of the world, especially sub-Saharan Africa, still face chronic hunger due to low food production. This can be due to low fertility soils, and/or lack of sufficient land. Many such areas are also anticipated to be most severely affected by global environmental change (GEC), and especially climate change (Parry et al. 2005; Lobell et al. 2008). Nevertheless, this shift over recent decades towards a more integrated food security concept challenges the research community to think more broadly than food production alone. It raises questions ranging from overarching issues related from frameworks for conceptualising food security and identifying GEC-related and other key limiting factors which determine it, to more detailed issues related to specific research foci to overcome them. This paper lays out a case for a food systems framework to help address the overarching issues and identify the limiting factors and how they interact. It also provides a number of examples of how selected elements of the framework can help define varied aspects of food security research to address these limiting factors.

## Food security research approaches

In addition to highlighting the importance of access to food, the more holistic concept that recent definitions of food security embody identify a wide range of research challenges spanning the humanities and social and economic sciences, rather than just biophysical sciences (Pálsson et al. 2011). There is however still a predominant research emphasis on increasing crop productivity, i.e. yield (biomass/unit area); a search on Google Scholar on 1st June 2011 for articles published between 2005 and 2011 with the words "crop yield" or "access to food"/"food access" in the title identified 1360 and 230 references, respectively. Given the need to produce more food this is of course very important, but it is also driven by the momentum of research in this area. As most of our food comes from crops, research has historically concentrated on agronomy (usually focussed on the experimental plot or field level, and usually for a single cropping season) and its associated sciences, although livestock and fisheries also received considerable attention. This research has been vitally important and has delivered a wide array of technological productivity advances; average yields of the world's main grains (wheat, barley, maize, rice and oats) have increased three-fold since 1960, although increases for coarse grains (millet, sorghum) and root crops (cassava and potato) have been nearer level (FAO 2009). When adopted over a large area these technological advances have led to greatly enhanced production.

These advances have not been without significant environmental cost, and there is now a strong drive to reduce negative externalities such as soil degradation, water pollution, loss of biodiversity and greenhouse gas emissions. Nonetheless, and driven by recently increasing concerns about population growth and rising incomes leading to changing diets, the main motive for most agricultural research remains the need to yet further increase food production. However, and as pointed out above, the fact that so many people are still facing food insecurity despite global production currently being sufficient for all, indicates that research which considers multiple aspects of food security and food systems is needed. How can the research 'powerhouse' be better geared towards the needs of the upcoming decades, especially given anticipated changes in climate and other environmental and socioeconomic factors?

Agronomic research is undoubtedly still vitally important, and the author and colleagues outlined three major challenges for agronomists in the climate/food security debate: (i) to understand better how climate change will affect cropping systems (i.e. the arrangement in which various crops are grown together in the same field, as opposed to crop productivity); (ii) to assess technical and policy options for reducing the deleterious impacts of climate change on cropping systems while minimizing further environmental degradation; and (iii) to understand how best to address the information needs of policy-makers and report and communicate agronomic research results in a manner that will assist the development of food systems adapted to climate change (Ingram et al. 2008). In addition, to contributing more effectively to the food security/ environmental change debate, the agricultural research community should more actively consider how to translate findings at plot-level over a few seasons to larger spatial and temporal levels and thence to the issues of food security. Methods for estimating *regional* production–and especially how it will change in future–are still relatively weak, with analyses mainly relying on statistical approaches or extrapolation from mechanistic point models, although mechanistic modelling approaches also exist (e.g. Parry et al. 2005; Challinor et al. 2007).

While research on producing food has allowed remarkable gains to be made, the dominance of this research community has overshadowed many other important aspects of research related to the full food system. However, while production increase continues to be an important goal, other activities such as processing food, packaging and distributing food, and retailing and consuming food are now all receiving increased attention, and the whole food chain concept ("farm-to-fork" or "plough-to-plate") is now well established (Maxwell and Slater 2003; ESF 2009). This concept not only helps to identify the full range of activities involved in the food system, but also helps to identify the actors involved, the roles they play, and the many and complex interactions amongst them (Ericksen et al. 2009).

A different approach to the food chain concept for food security research focuses on the substance of the definition from the 1996 World Food Summit, *vis*. food availability, food access, food utilisation and their stability over time (FAO 1996; Stamoulis and Zezza 2003). These components are clearly different from the activities of producing, processing, distributing, etc. which characterise the food chain literature; rather than focussing on the "what we do" (i.e. the activities), they emphasise the "what we get" (i.e. the *outcomes* of these activities which collectively underpin food security).

While individual actors in the food system are of course primarily interested in their specific activity (i.e., food producing, processing, distributing, etc.) people not involved in these activities are essentially only interested in the food security outcomes of the activities (rather than in the activities per se). Research, however, needs to recognise that the technologies and policies that influence the manner in which all the activities are implemented directly affects the overall food security outcomes. This important point is discussed further below in Example 2: "Analysing the consequences of interventions on food security outcomes".

## The 'food system' concept and its development for GEC research

In the late 1990s, as research interest within the international GEC research community grew on the interactions between GEC and food security, it became increasingly clear that the complexity of the issues involved needed a new approach; focus needed to move beyond the impacts of climate change on crop productivity (which had largely dominated GEC-food research to date). An innovative research agenda needed to clarify and frame (i) how GEC affects food security, (ii) how to adapt to the additional stress GEC brings, and (iii) how to implement our efforts so as to minimise further drivers of GEC. Based on a better understanding of what constitutes food security, members of the GEC research community charged with developing the new agenda agreed that research should be based on 'food systems' (Gregory and Ingram 2000; Ingram and Brklacich 2002).

The food system concept was not new: driven by social and political concerns, rural sociologists had promoted this approach for some years (e.g. McMichael 1994; Tovey 1997). Several authors have since put forward frameworks for analysing food systems, but Sobal et al. (1998) noted that few existing models broadly described the system and most focused on one disciplinary perspective or one segment of the system. They identified four major types of models: food chains, food cycles, food webs and food contexts, and developed a more integrated approach including nutrition. Dixon (1999) meanwhile proposed a cultural economy model for understanding power in commodity systems, while Fraser et al. (2005) proposed a framework to assess the vulnerability of food systems to future shocks based on landscape ecology's 'Panarchy Framework'.

Despite these varied approaches, none was suitable for drawing attention to, let alone analysing, the two-way interactions between the range of food systems activities and food security outcomes, and the full range of GEC of parameters. This was needed as adaptation to climate change and/or to other environmental and socioeconomic stresses, means 'doing things differently'. In relation to food systems, the 'things' that need to be done differently are the activities, i.e. the aspects that can be adapted are the methods of producing, processing, distributing food, etc., and adaptation options in all these need to be considered.

A new approach was needed for GEC research and for the GEC community this was a clear departure from the food-related research which had hitherto concentrated on agro-ecology (Gregory et al. 1999). The food system approach thus characterised a new, interdisciplinary food security research project (Global Environmental Change and Food Systems, GECAFS) within the international GEC Programmes (GECAFS 2005; Ingram et al. 2007). Drawing on the extensive (yet relatively distinct) literatures built up by the food chain and food security communities, respectively, a key paper by Polly Ericksen (Ericksen 2008a) formalised the 'GECAFS food systems' concept (Fig. 1; Box 1).

**Box 1.** Food system *Activities* and food security *Outcomes* (derived from Ericksen 2008a; Ingram 2009; Ericksen et al. 2010a)

Food systems encompass a number of *Activities* which give rise to a number of food security *Outcomes.*

Food systems *Activities* include: (i) producing food; (ii) processing food; (iii) packaging and distributing food; and (iv) retailing and consuming food. All these activities are determined by a number of factors ('determinants'). The determinants of 'packaging and distributing' food, for instance, include the desired appearance of the final product and other demands of the retailer, the shelf life needed, cold chain and/or other transportation infrastructure, road, rail and shipping infrastructure, trade regulations, storage facilities, etc. (Fig. 1).

Undertaking these activities leads to a number of *Outcomes*, which not only contribute to food security, but also relate to environmental and other social welfare issues (Fig. 1).

Both the activities and their outcomes are influenced by the interacting GEC and socioeconomic 'drivers'; and the environmental, food security and other social outcomes of the activities feedback to the drivers (Fig. 2).

***The food system Activities***

Food system activities are grouped into four categories in Fig. 1. Each has its own set of actors that control each activity. Some actors (e.g. major supermarkets) span several activities:

Producing food includes all activities involved in the production of the raw food materials. Key factors include farmers, hunters, fishermen, the multiple suppliers of production inputs including agrichemicals, agricultural labourers, and land owners.

Processing and Packaging food includes the various transformations that the raw food material (e.g. grain, vegetable, fruit, animal) undergoes before it is sent to the retail market for sale. Key factors include the middlemen who buy from producers and sell to processors; the managers and workers in processing and packaging plants; and trade organisations that set standards.

Retailing and distributing includes a range of middlemen who go between the producers, processors, packers and the final markets, and the many actors involved in e.g. transport, delivery and warehousing operations, advertising, trading and supermarkets.

Consuming includes all consumers themselves, and the varied actors that control what they consume, e.g., market regulators, advertisers, consumer groups.

***The food security Outcomes and their elements***

Food security outcomes are grouped into three components (Availability, Access and Utilisation), each of which comprises three elements (Fig. 1). All nine elements are either explicit or implicit in the FAO definition above (FAO 1996); all have to be satisfied and stable over time for food security to be met.

*Food Availability*

- Production = how much and which types of food are available through local production.
- Distribution = how food is made available (physically moved), in what form, when and to whom.
- Exchange = how much of the available food is obtained through exchange mechanisms such as barter, trade, purchase, or loans.

*Access to food*

- Affordability = the purchasing power of households or communities relative to the price of food.
- Allocation = the economic, social and political mechanisms governing when, where and how food can be accessed by consumers.
- Preference = social, religious or cultural norms and values that influence consumer demand for certain types of food.

*Food Utilisation*

- Nutritional value = how much of the daily requirements of calories, vitamins, protein, and micronutrients are provided by the food people consume.
- Social value = the social, religious and cultural functions and benefits food provides.
- Food safety = toxic contamination introduced during producing, processing and packaging, distribution or marketing food; and food-borne diseases such as salmonella and CJD.

While enhancing food security may often be the prime motive when planning adaptation strategies for the additional stresses GEC is bringing, Fig. 1 shows that the food system activities also give rise to other outcomes. These relate to other socioeconomic issues and conditions, and to the environment, and all have feedbacks to the food system drivers (Fig. 2); while many factors not directly related to the food system (e.g. fossil fuel use generally, urbanisation) drive GEC, landuse change, intensified agricultural practices, overexploitation of fisheries, food processing and transport, etc. are all major drivers of GEC (see Example 4, below). What might be 'good' adaptation for food security might also be good for other socioeconomic and/or environmental outcomes–but it might also be worse; synergies and trade-

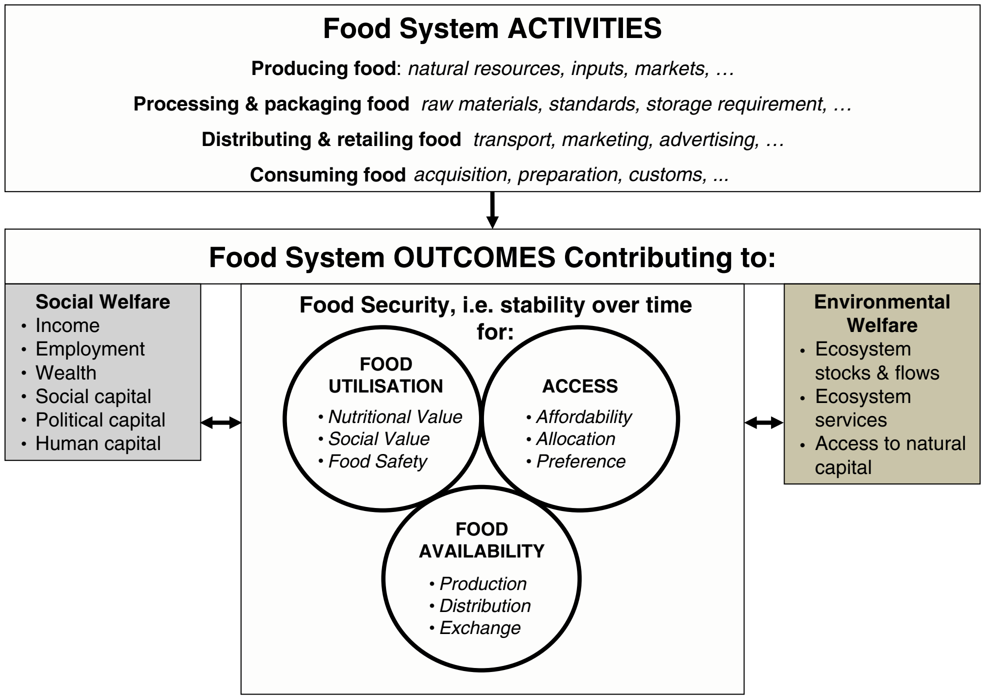


**Fig. 1** Food system *Activities* and *Outcomes*

offs need to be carefully considered, although the complexity of the food system makes analyses difficult. However, the current evidence of food insecurity and environmental degradation suggests that mal-adaptation may already be occurring (Ericksen et al. 2010b). The key questions are (i) which activity(s) should we best seek to adapt to improve food security for given situations; (ii) what will be the consequences of such adaptation strategies for the full set of food security elements; and (iii) what will be the synergies and trade-offs among the three food system outcomes and the feedbacks to food system drivers? Being highly aggregated the food system framework (Fig. 2) cannot answer these questions per se, but it is useful for generating hypotheses that can be further explored using other more specific methods.

The GECAFS food systems approach was specifically designed to help GEC research, and analyses of the impacts of

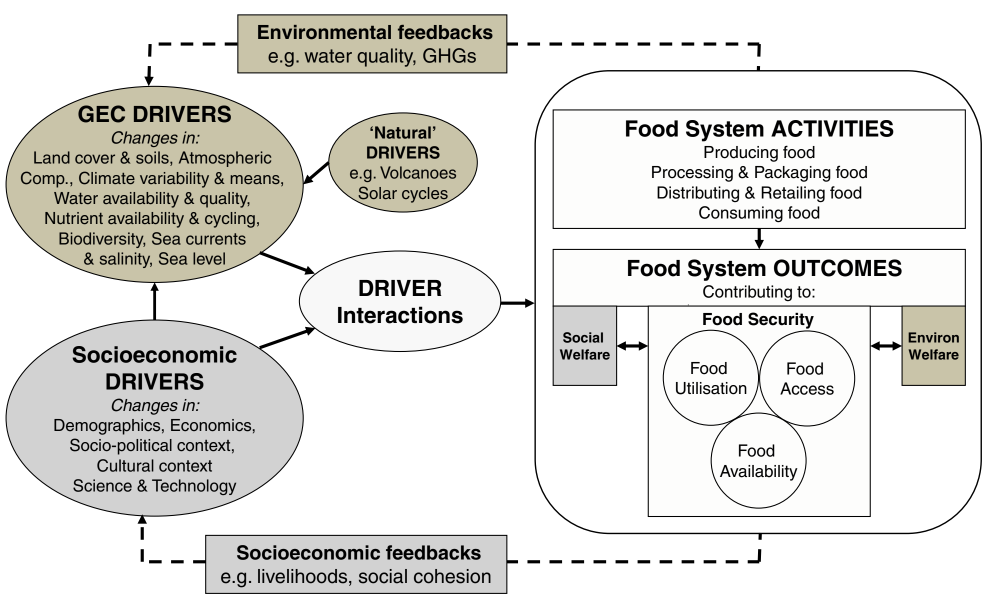


**Fig. 2** Food system drivers and feedbacks

changed biophysical environmental 'drivers' on food production are increasingly important, especially now that evidence has emerged of reduced yields worldwide due to climate change (Lobell et al. 2011). The approach however also notes that while a wide range of socioeconomic 'drivers' also need to be included in food security analyses, it is the interactive impact of these two sets of drivers that affects how the food system operates and hence how the food security and other outcomes manifest (Fig. 2). Both the GEC and socioeconomic drivers can be (and usually are) a combination of local and non-local in origin. Global-level forces such as climate change, trade agreements, and world price for energy and food will affect local and regional food systems; land rights, local market policy, natural resource degradation and other local factors will affect the resilience of local food systems to these external, and also internal, stresses.

The food systems approach not only helps to engender discussion of adaptation options across the full set of food system activities (i.e. along the length of the food chain) rather than just, say, in the agricultural domain, but also provides a framework for systematic analysis of synergies and trade-offs, balanced across a range of societal goals. Further, it serves as a 'checklist' to ensure the range of outcomes (some hitherto unforeseen) is being considered by those planning and/or implementing adaptation.

In addition to broadening the debate from the relatively-narrow, biophysical research on impacts of climate change on crop growth, the GECAFS food system concept was specially designed to enhance interdisciplinary research on the two-way interactions between GEC and efforts to meet food security. Integrating the notions of food system activities with food security outcomes (Fig. 1), the GECAFS food system concept provides a framework for designing research to systematically analyse a wide range of GEC-food security interactions and questions. It has proven robust across a range of socioeconomic and geographical contexts, strengthened by the recognition of the range of 'scales' and 'levels' inherent in modern food systems. 'Scale' is the spatial, temporal, quantitative, or analytical dimensions used to measure and study any phenomenon, and 'levels' is the units of analysis that are located at different positions on a scale (Gibson et al. 2000; Cash et al. 2006). A predominant feature of 21st Century food systems is that they are inherently cross-level and cross-scale (Ericksen et al. 2010a).

The following examples illustrate the utility of this food system concept for improving understanding of vulnerability of food systems to GEC; analysing the consequences of technical interventions on food security outcomes; analysing the consequences of food system activities for environmental parameters; framing scenario analyses; and analysing the food security dimension in international environmental assessments.

**Example 1: analysing the vulnerability of food systems to GEC and identifying adaptation options**

There is a rich and diverse food security literature addressing the vulnerability of individuals and/or households to a range of stresses including GEC (e.g. Adger 2006; Ericksen 2008b; Misselhorn et al. 2010). By considering the whole food system, it is possible to identify where vulnerability arises within the full range of food system activity 'determinants', i.e. the factors that determine how a given food system activity in undertaken/operates (Eakin 2010; Box 1). Focussing on these, rather than the food security outcomes per se, helps indicate what, where and how adaptation measures to enhance food security in the face of GEC might be most effective. Further, looking across all food system activities offers the chance of identifying intervention points that might not be apparent if, for instance, one only considers the agricultural aspect. This is exemplified by a case study of the vulnerability of district-level food systems to GEC in the Indo-Gangetic Plain.

Major investment in infrastructure has allowed Ludhiana District of the Indian Punjab to developed very effective irrigated agriculture, but excessive ground water extraction (a locally-significant environmental change) has significantly lowered water tables, thereby reducing irrigation supply. This will be exacerbated by anticipated changes in rain and glacier melt, leading to a major vulnerability point relating to producing food. This, in turn threatens the 'producing food' activity, affecting the overall food production at the District-level and hence the 'availability' component of food security (Fig. 1). In contrast, in the Ruhani Basin District in Nepal's Terai region, where food production has historically often suffered from poor harvests, local food security depends on the ability to move food from village to village, especially in times of stress. Food distribution infrastructure is however not robust, and increased flooding due to GEC-induced potential glacier melt coupled with more extreme weather will disrupt footpaths, bridges and other vital aspects, affecting the 'distributing' activity, and thence the distribution element of food availability (Fig. 1). The food system approach identified the principle vulnerability points in the two Districts and shows them to be quite different. They will need very different adaptation responses to reduce their respective vulnerabilities. Improved water governance would reduce the food system vulnerability in the Indian case (Aggarwal et al. 2004), while in the Nepali case, investment in infrastructure and policies for strategic food reserves at local level are needed (Dixit 2003).

Adaptation options to reduce food system vulnerability tend to focus on technical interventions to increase food production. By and large, and as noted above, these are targeted at increasing yields of crops, livestock or fish, and are important in many parts of the world, especially sub-Saharan Africa. These are complemented by advances in food storage, processing and packaging which have helped limit post-harvest losses and combat food waste. However, and as the Indian and Nepali cases show, options to adapt to the additional stresses that GEC will bring also need to be vigorously explored in the policy domain. These may be particularly effective when considered at regional level and over multiple years (Liverman and Ingram 2010). Examples include establishing strategic grain reserves for a region, harmonizing regional trade and quarantine agreements, introducing water pricing and agreeing the sharing of water and other natural resources (Aggarwal et al. 2004; Drimie et al. 2011). Other options related to improving regional infrastructure, such as road, rail and harbour facilities allow the rapid movement of food in a crisis. These all need to be considered when seeking ways to reduce the vulnerability of the food system to GEC, and the GECAFS framework helps to remind researchers and decision-makers of the wide range of potentials interventions that need to be considered.

### Example 2: analysing the consequences of interventions on food security outcomes

Example 1 discusses the identification of food system 'vulnerability points' and considers adaptation interventions in different food system activities (producing food and distributing food). When discussing adaptation interventions in response to GEC, it is important to explicitly state how a given intervention to a food system activity will affect the 'target' food security element. While adapting agronomic practice can have direct and clear impact on increasing food production, the impacts of more novel technologies on other food security outcomes may be less obvious, especially when applied to other food system activities. These include information and telecommunications (ITC) technologies which are playing ever-increasing roles in food systems. Although perhaps less relevant to developing world situations (at least at present) they will likely constitute important tools in the basket of adaptation options. Examples already seen range from GIS technologies for fertilizer applications (Assimakopoulos et al. 2003) and laser technologies for field levelling (Jat et al. 2006) to radio-frequency identification (RFID) for traceability of produce though the food chain (Kelepouris et al. 2007) and low-cost detection of allergens in food stuffs (Bettazzi et al. 2008).

ICT technologies (as with all technologies) are applied to food system activities, affecting the ways in which food producing, processing etc. are conducted. How will the application of ITC technologies affect the food security outcomes?

An initial analysis to address this question was conducted at a COST (European Cooperation in Science and Technology) workshop held in Bruges, Belgium in June, 2009. The GECAFS food system framework of four groups of food systems activities and nine elements of food security outcomes (Fig. 1) was used to systematically identify examples of (i) how the application of example ICT technologies could be implemented in different food system activities, and (ii) how these could affect a range of food security outcomes. A number of the examples are presented in a matrix of activities vs. outcomes (Table 1).

By clearly identifying the full set of food system activities and example elements of the food security outcomes (Fig. 1), the GECAFS food system approach provided the structure for a matrix (Table 1) to systematically identify possible impacts of example ITC technologies on food security outcome. It details the way a given ICT technology can be applied to a given food system activity and how this in turn affects specific food security elements.

### Example 3: food system concepts for framing scenarios analyses

Scenarios are "plausible and often simplified descriptions of how the future may develop, based on a coherent and internally consistent set of assumptions about key driving forces and relationships" (MA 2005a). Scenarios are neither forecasts of future events, nor predictions of what might or will happen in the future. Rather, they develop and present carefully structured stories about future states of the world that represent alternative plausible conditions under different assumptions.

Scenario exercises are increasingly being used to help decision makers and other stakeholders address the 'big picture', complex challenges given future uncertainty. While the future of food production poses substantial questions (and hence is the focus of considerable research effort, as discussed above), the future of food security is even more complex. This is due to two main factors. First, the individual nature of the food system drivers (demand, trade arrangements, climate, etc.; Fig. 2) is uncertain, let alone the critically-important interactions among them. Second, food security is itself complex: it has nine major elements all of which need to be satisfied (Fig. 1), and all of which will vary depending on the future interactions of the drivers with the food system.

The nine food security elements (Fig. 1) (as opposed to just production) were all included in a prototype scenario study in the Caribbean (GECAFS 2006). This region is highly dependent on external food sources, exposed to extreme weather events and is in the process of implementing a new regional trade system (CARICOM Single Market and Economy, CSME). Further, as elsewhere, there are considerable uncertainties associated with all the food system drivers

**Table 1** Indicative analysis of the method (in **bold**) by which the application of example ITC technologies (in *italics*) in different food system activities (columns) could affect a range of food security outcomes (rows). (From Ingram, Barling and Gobius, unpublished)

| | Producing food | Processing/packaging food | Distributing/retailing food | Consuming food |
|---|---|---|---|---|
| Food production | *Automated lab experiments and micro arrays in plant technology* to **screen potential traits/genes** | *Sensors and automation* for **better quality control in food processing** | | *Web connectivity* to **enable social consumer networks to inform producers** |
| Food distribution | *Satellite data, GIS and high performance computing* for **forecasting better crop failure for emergency food aid planning** | | *RFID tags* to **improve logistics** | *e-commerce* to **enable internet ordering and instant delivery** |
| Food affordability | *GIS for improved input use efficiency* to **reduce costs of production** | *Low cost print technologies* to **reduce packaging costs** | | *Web connectivity* to **enable social consumer networks to inform other consumers** |
| Food exchange | *Cell phone technology* to **help artisanal fishers find best local market** | *RFID tags* to **improve value chain management** | *Secure e-commerce* to **enable trusted trade data exchange** | |
| Food safety | | *Smart packaging* for **spoilage identification** | *Sensors and automation* for **monitoring cold chain and storage conditions** | *Low cost detection kits* for **scanning for food contaminants** |

(Fig. 2) so the scenarios approach was advocated. The key interest to regional policy makers, researchers and resource managers was how a range of different plausible futures would affect the food security of the region.

The scenarios exercise involved four main steps: (i) key regional GEC and policy issues were identified through stakeholder consultation workshops involving regional scientists and policymakers; (ii) a set of four prototype

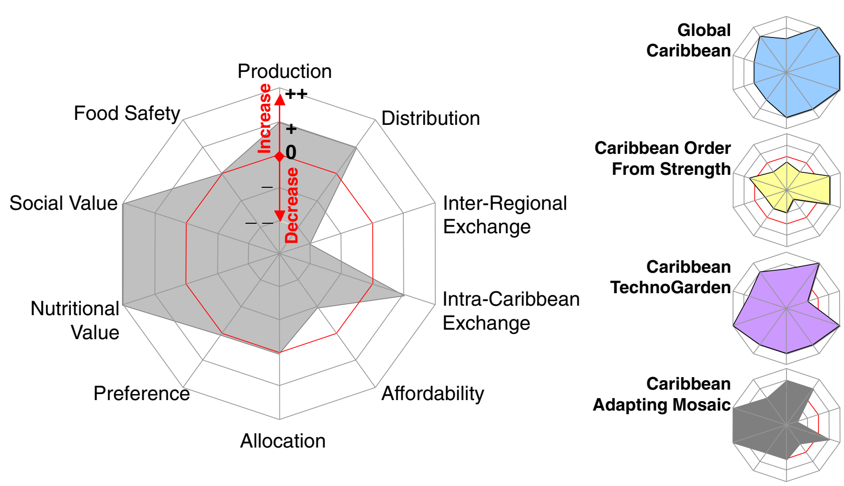


**Fig. 3** Outcomes for 10 variables that collectively determine food security for four plausible futures for Caribbean food systems (reproduced from Ingram and Izac 2010, with permission). A rating of (++) indicates a high increase (i.e. outermost ring in the chart) and a rating of (+) to some increase (i.e. the second outermost ring in the chart). Conversely, a rating of (− −) implies high decrease (i.e. the innermost ring of the chart) and a rating of (−) reads as some decrease (i.e. the second innermost ring of the chart). Finally, a rating of (o) translates to no changes versus the current situation and a rating of (+/−) shows mixed trends with some increase in some aspects alongside decreases in others (i.e. both are depicted by a value on the '*heavy line*' centre ring) (GECAFS 2006)

regional scenarios were drafted based on the broad rationale, assumptions and outcomes of the MA scenarios exercise (MA 2005a), but allowing for regional deviation where needed; (iii) developments to 2030 per scenario for key each food security determinant (Fig. 3; see GECAFS 2006 for full details of the method). It must be noted that scenarios are not predictions but analyses of how plausible futures may unfold.

The use of the GECAFS food system approach can also be found in the scenarios exercises for the CGIAR's new Consortium Research Project 7 "Climate Change, Agriculture and Food Security" (CCAFS). Here the objective is to identify viable technical and policy interventions to adapt agriculture and food systems to climate change so as to improve outcomes for food security, livelihoods and environmental benefits (CCAFS 2009). Scenarios exercises are being conducted in each of the three initial research regions (East Africa, West Africa and the Indo-Gangetic Plain). In order for potential synergies and trade-offs between these three outcomes to be assessed a small number of elements (variables) for each of these three outcomes had to be agreed. Using the food system approach as a framework, regional stakeholders identified four critically-important elements for the region's food security, for environmental factors, and for livelihoods. Food security elements included (i) the affordability of staple foods; (ii) the regional production of staple foods; (iii) the effectiveness of distribution mechanisms; and (iv) the nutritional value of staple foods (CCAFS Scenarios Team 2010).

This CCAFS example highlights an important point about the framework: it serves as base that can be further developed to be more useful and specific in a dynamic context, which can lead to a number of valuable research avenues. The framework is qualitative and more quantified analyses will be needed for many discussion-making processes. For instance, a range of models aimed at quantifying (as far as possible) the four food security elements is being identified by the CCAFS group with a view to 'driving' the axes of the spidergrams exemplified in Fig. 3 (CCAFS Scenarios Team 2010). The aim is to model how each variable (axis) evolves over time for each scenario, noting changes both within and between different scenarios, with a view to including the impact of technical and/or policy interventions over time.

These scenario exercises deliver a number of related outputs related to Fig. 3: they provide (i) an analysis of all elements of food system outcomes (multiple axes on graphs); (ii) an assessment of how each outcome determinant would change (change of position along axes); (iii) ability for a policy interpretation of different future conditions (comparing graphs); and (iv) adaptation insights at the regional level for improving overall food security (where to concentrate effort on enlarging the polygon areas of each graph). They also brought together a wide range of specialists and representatives of the many stakeholders involved in food systems who hitherto had not interacted. It should be noted, however, that the purpose of these initial scenario exercises was to investigate food security outcomes of plausible futures. They were not designed to determine adaptation pathways, which should form the subject of follow up research.

### Example 4: quantifying the contribution of food system activities to crossing 'planetary boundaries'

Many human activities affect environmental conditions, degradation of which will undermine the natural resource base upon which food systems are founded. This example discusses how food system activities affect environment (the 'feedback'; Fig. 2), and is based on the notion of 'planetary boundaries'. These define the safe operating space for humanity with respect to the Earth system and are associated with the planet's biophysical subsystems or processes. If these thresholds are crossed, then important subsystems, such as a monsoon system, could shift into a new state, often with deleterious or potentially even disastrous consequences for humans (Rockström et al. 2009; Fig. 4). Identifying and quantifying 'planetary boundaries' that must not be transgressed therefore help prevent human activities from causing unacceptable environmental change.

One of the most–perhaps *the* most–ubiquitous human activity relates to striving to attain food security and from a 'food' perspective agriculture is usually thought of as the cause for concern; 12–14% of total greenhouse gas (GHG) emissions are attributed to agriculture and a further 18% attributed to land-use change and forestry (much of which is related to clearing land for agriculture and pasture) (Foresight 2011). However, all food system activities lead to GHG emissions and Edwards et al. (2009) estimated that in the US food system, only 60% of GHG emissions can be attributed to producing food; 40% are due to the other food system activities. But GHG emission is not the only environmental consequence of food systems. Impacts on biodiversity, on biogeochemical cycles, on fresh water resources and on other environmental parameters are all in part caused by food system activities (Fig. 2).

Table 2 shows a matrix of the four sets of food system activities against eight of the 10 planetary boundaries ('ocean acidification' and 'stratospheric ozone depletion' are not included as they were not quantified).

Rather than being confined to impacts of agriculture, Table 2 gives examples in almost all cells of the matrix; almost all food system activities contribute to 'crossing the boundaries'.

Food processing leads to a range of wastes which exhibit large amounts of organic materials such as proteins, carbohydrates, and lipids; large amounts of suspended

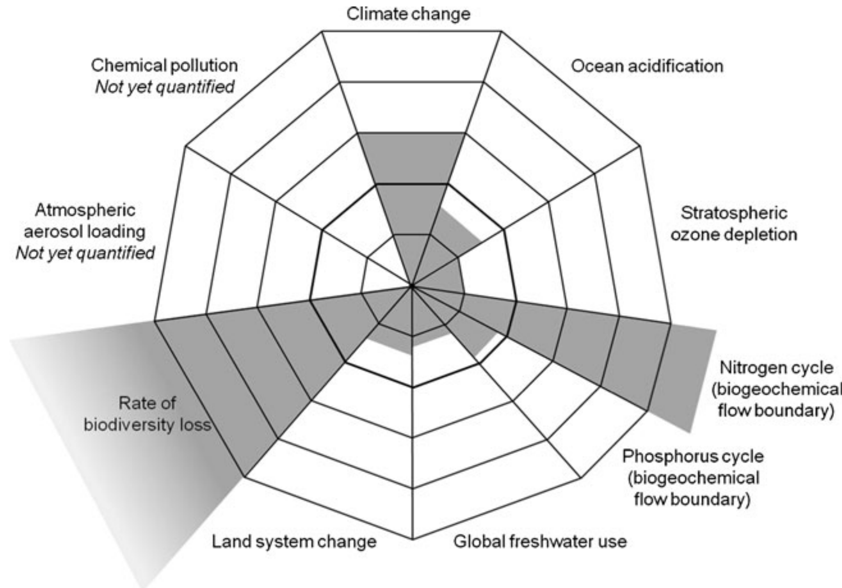


**Fig. 4** Nine 'planetary boundaries' which, if crossed, could generate unacceptable environmental change. The area inside the *heavy line* represents the proposed safe operating space for nine planetary systems. The *shaded wedges* represent an estimate of the current position for each variable. The boundaries in three systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle) have already been exceeded (Rockström et al. 2009). (Figure reproduced from Liverman and Kapadia 2010, with permission)

solids (depending on the source); high biochemical oxygen demand (BOD) and/or chemical oxygen demand (COD); high N concentration; high suspended oil or grease contents; and high variations in pH. Most have higher levels of these contaminants than municipal sewage (Kroyer 1995). Food processing plants have been found to be responsible for 4.7% of total manufacturing intake of fresh water (Dupont and Renzetti 1998).

Food packaging requires paper and card (which both demand land use change for pulp production, with consequences for forestry operations affecting biodiversity and pollution); plastics (which have both high real and virtual carbon contents); and aluminium and steel (which can affect biodiversity through the construction of hydro-electricity schemes for smelting bauxite and iron ore). Transporting food also makes a large direct contribution to GHG emission and the notion of 'food miles' receives considerable attention in the scientific and more general media. Food transport for the UK, for example, produced 19 Mt $CO_2$ in 2002, of which 10 Mt were emitted in the UK (almost all from road transport) (Spedding 2007). Over 2 Mt $CO_2$ is produced simply by cars travelling to and from shops (Food Climate Research Network 2011). In retailing, refrigerant leakage from fridges and freezers accounts for 30% of super-markets' direct GHG emissions (Environmental Investigation Agency 2010), while preparing food also contributes significantly to GHG emissions, with 23% of energy use in commercial kitchens devoted to cooking, 19% to water heating and 19% to space heating (CIBSE 2009).

**Table 2** Matrix giving examples of how the four sets of food system *Activities* (columns) contribute to crossing eight of the 10 planetary boundaries (rows)

| | Producing food | Processing & packaging food | Distributing & retailing food | Consuming food |
|---|---|---|---|---|
| Climate change | GHGs from fertilizers; changing albedo | GHGs from energy production | GHGs from transport and refrigeration systems | GHGs from cooking |
| N cycle | Eutrophication and GHGs from fertilization | Effluent from processing and packaging plants | NOx emissions from transport | Food waste |
| P cycle | P mining for fertilizers | Detergents from processing plants | | Food waste |
| Fresh water use | Irrigation | Washing, heating, cooling | | Cooking, cleaning |
| Land use change | Extensification and intensification | Deforestation for paper/card | Transport and retail infrastructure | |
| Biodiversity loss | Deforestation, hunting, fishing | Hydroelectricity dams for aluminium smelting | Invasive species | Consumer choices |
| Atmospheric aerosols | Smoke and dust from land-use change | | Emissions from shipping | |
| Chemical pollution | Pesticides | Effluent from processing and packaging plants | Transport emissions | Cooking, cleaning |

Finally, it is well worth noting that much of the GHG emission could be reduced across the whole food system if less food was wasted by consumers. Parfitt et al. (2010) report that 25% of food purchased (by weight) is wasted in UK households and the 8.3 Mt of food and drink wasted each year in the UK has a carbon impact exceeding 20 Mt of $CO_2$-equivalent. Reducing food waste by only 25% in the USA would reduce $CO_2$-equivalent by 65 Mt annually (Lyutse 2010).

Many studies assess the impact of a given food system activity (e.g. producing or transporting food) to a given environmental outcome (e.g. GHG emissions). The food system concept provides a framework to integrate such studies to provide a more complete description of the 'food' contribution to crossing the planetary boundaries.

### Example 5: analysing the food security dimension in international environmental assessments

The final example shows how the notion of a full set of food security outcomes (cf. Box 1) has been used to analyse the completeness of international environmental assessments in regard to food security. As a contribution to the GECAFS synthesis (Ingram et al. 2010), Stanley Wood and colleagues reviewed the goals and outputs of major international assessments that have examined the linkages between environment and food. The analysis included the Millennium Ecosystem Assessment (MA 2005b), the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (IPCC 2007) and Global Environment Outlook 4 (UNEP 2007). Particular attention was played to the treatment of food systems, as well as to the extent to which the key implications of GEC for global and local food security were articulated and explored (Wood et al. 2010).

Relevant factors were extracted from the three assessments that had been treated in one or more assessments, and which pertained to: environmental conditions; environment-related stresses that have relevance for food system functioning; food system measures of performance; and food security outcomes. These factors are grouped and displayed in the four columns in Fig. 5. The figure also indicates the linkages flowing from left (environment condition) to right (food security outcomes) that received attention in the assessments.

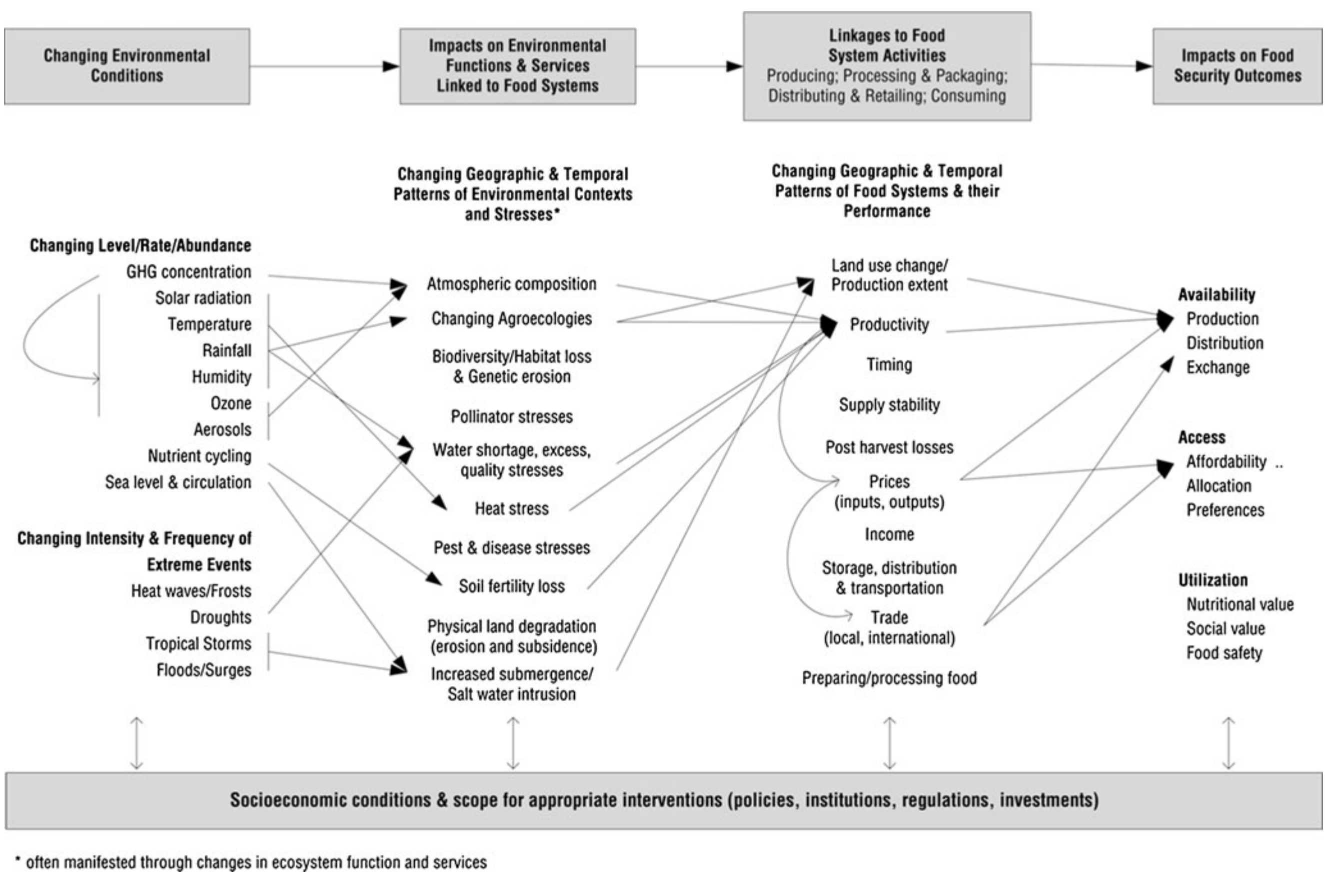


**Fig. 5** Environmental change, food system, and food security outcome components and dynamics: highlighting concentration of issues and pathways addressed by assessments (reproduced from Wood et al. 2010, with permission)

While noting their analysis is "inescapably qualitative and subjective in its formulation", Wood and colleagues highlight a number of issues concerning the relative strengths and weaknesses of the assessments undertaken: (i) producing food is the single most dominant food system component and, specifically, GEC-induced impacts on productivity; (ii) many factors identified in the assessments were not explicitly linked to other factors of relevance to food security outcomes (there are fewer linkages moving to the right of Fig. 5); (iii) there appears to be systematic biases in knowledge and analytical capacity that are unrelated to the perceived importance of specific factors (e.g. pests and diseases and post-harvest losses are anecdotally very significant factors influencing food availability but they receive relatively little treatment); (iv) issues relating to seasonality and stability receive very little attention; and (v) there are substantial data, knowledge and expertise gaps related to processes influencing the non-supply-related food security outcomes.

The food system concept provided a 'checklist' to help structure this analysis, revealing assessments that have "fallen short, sometimes significantly, of providing comprehensive and balanced evidence on the range and interdependence of environmental change phenomena and on the consequences of change on the many facets of food systems and security" (Wood et al. 2010).

## Conclusions

Understanding the interactions between food security and global environmental change is highly challenging. This is nevertheless increasingly important as 50% more food will be needed by 2030 (Godfray et al. 2010b) and there are concerns that the risk of food insecurity will likely grow. These concerns are compounded by the simultaneous need to reduce negative environmental feedbacks from the ways we meet these demands. A further challenge therefore is developing food system adaptation pathways that are significantly more environmentally benign than current approaches. Adapting our food system activities to meet these challenges will give rise to changes in all food security outcomes to some extent (Fig. 1) but often researchers only consider one food security element, usually food production. A meaningful adaptation discussion on food security needs consideration of how any intervention will affect all other eight elements of the food security outcomes; in principle, any intervention, even if only targeted at only one element will affect all nine.

More effective policies, practices and governance are needed at a range of levels on spatial, temporal, jurisdictional and other scales (Cash et al. 2006; Termeer et al. 2010) and research has an important role to play in providing knowledge to assist these. Given the complexity of food security, especially in the context of GEC, this research has to develop systematically to be most effective. However, different research groups have differing interests and/or could be addressing differing information need for policy formulation. The overall framework–albeit depicted in general terms–helps to map where each effort contributes to the overall picture. The examples above show how this mapping can occur in practice, each relating to either the food system activities or the food security outcomes, and dealing with different areas of interest (i.e. vulnerability/impacts or adaptation or feedbacks).

When taken together (Fig. 1) and considered within (i) the notion of interacting GEC and socioeconomic drivers, and (ii) potentially positive and deleterious feedbacks to socioeconomic and/or environmental conditions (Fig. 2), the framework can bring further benefits. First, it provides a checklist to help ensure the necessary issues are included in dialogues aimed at enhancing food security (especially in the context of other goals) and identifies the range of actors and other interested parties who should be involved. Second, it helps assess the impacts of GEC on food systems by focussing on multiple vulnerabilities in the context of socioeconomic stresses. Third, it helps in determining the most limiting factors which lead to food insecurity, thereby identifying intervention points for enhancing food security.

Identifying which of the numerous interactions depicted in Fig. 2 to research, and how to bring them together would be highly complex without a framework. Most importantly, therefore, it provides a conceptual model to help identify research avenues for (i) integrated analyses of the full set of food system activities (i.e. producing, storing, processing, packaging, trading and consuming food) with those of the food security outcomes i.e. stability of food access, utilisation and availability, and *all* their nine elements (rather than just food production); and (ii) analysing feedbacks to the earth system (e.g. GHG emissions, impacts on biodiversity) from food system activities, integrating the "what we do" with the "what we get". By laying out an integrative socio-environmental approach for considering such feedbacks, it thus helps design research to analyse synergies and trade-offs between food security, ecosystem services and social welfare outcomes of different adaptation pathways.

It is important to discuss one final aspect. As mentioned above, the framework is depicted at a general level and cannot, in itself, assess the consequences of specific interventions. Its value is in helping to formulate plausible hypotheses that can and should be further explored through other methods. So, while acting as a checklist of what needs to be discussed, it only identifies a number of high-level issues; some specific issues, such as animal welfare (ESF

2009) or public attitudes to genetically modified foods, are of high priority in some parts of the world, and would need to be included or strengthened for specific studies. To this end, individual research projects need to establish detailed agendas in the context of the overall framework.

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