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Review

Proposing an interdisciplinary and cross-scale framework for global change and food security researches

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ABSTRACT

Food security is greatly affected by the consequences of global change, especially its impact on agriculture. Currently, global change and food system interaction is a hot issue across the scientific community. Scientists have tried to explain this interaction from different perspectives, and the issues related to this interaction can be classified as (1) crop yield and productivity in response to global change; (2) crop distribution and allocation in relation with global change; (3) general impacts on food security. However, most of the existing studies lack consistency and continuity. As food systems exist at the intersection of the coupled human and natural system, the interdisciplinary context of global change and food security requires an integrated and collaborative framework for better describing their importance and complexity. To do so, we decompose global change/food security studies into different levels in accordance with the previous mentioned issues, field, regional, and global, and categorize them into the life sciences, earth and environmental sciences, and social and sustainability sciences, respectively (yet not necessarily one to one correspondence). At the field level, long-term observations and controlled experiments in situ are important for exploring the mechanism of how global change will affect crop growth, and for considering possible adaptation methods that may maximize crop productivity. At the regional level, priority should be given to monitoring and simulating crop production (animal production and fishery are not included here) within large areas (a region or a continent). At the global level, food security studies should be based on scenario assessments to prioritize human adaptations under the changed environment, using integrated socioeconomic–biogeophysical measures.

Contents

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1. Introduction

The Food and Agriculture Organization of the United Nations (FAO) defines a food-secured world as "a situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life". Unfortunately, our planet is currently food insecured with approximately 1 billion people undernourished globally (FAO, 2011). According to the United Nations Population Fund (UNFPA), the world population has exceeded 7 billion in October 2011. It is estimated that by 2050, this number is likely to reach 9 billion. In addition, there will be 2 billion to 3 billion more people with three times more per capita income, consuming twice food as much as now (Clay, 2011). The situation of population growth and dietary change will result in an overwhelming demand for food in the future.

If the effects of global environment change are taken into account on food production, that challenge grows even more daunting. Climate change threatens agricultural productivity in many regions around the world (Nelson et al., 2010). On our finite planet, most of the land that is suitable for growing food is already in use, but agricultural expansion is still ongoing in some developing economies, at the large cost of natural habitat and biodiversity loss (Godfray, 2011). In contrast, some high quality farmlands are converted into non-food uses, including human settlement, animal feed, seed, bioenergy and other industrial products (Foley et al., 2011). In addition to land degradation, water shortage and other severe environmental constraints, human is facing unprecedented pressures.

In the face of challenges, food production must grow substantially as a priority for processing, distributing, preparing, and consuming food in the human society. Some studies suggest that, in the best of circumstances, current crop production is needed to be doubled again[1] to keep pace with future global food demand (Foley et al., 2011). Information about the actual and potential impacts of global change on food supply is badly needed by policymakers to plan. In this context, scientists from various fields are responsible in quantifying the complex interactions among environment, agriculture, and food security for making sustainable solutions. Can science feed the world? To date, the issue of global change and food security has been widely discussed by the scientific community.[2]

Although many endeavours were made for tackling the issue, there are still no significant interdisciplinary and collaborative efforts. Scientists often restrict themselves to their area of speciality and exchange little knowledge and information to others. With so much at stake, researches relating to this context require a collaborative framework that involves interdisciplinary integration at multiple scales. In this case, we reviewed a wide range of recent relevant studies, trying to put forward a feasible framework that can address global change and food security issue as a whole—in respect of crop productivity, crop production, and food system vulnerability. The paper is organized by discussing global change and food security issue from both a multi-system perspective and an interdisciplinary perspective in the first place. Then a cross-scale framework is proposed for carrying out specific researches at different levels and different disciplines. Outcomes at each research level should be integrated for comprehensive assessment.

2. Global change and food security: a multi-system perspective

Since the beginning of human history, humans have continuously interacted with natural systems. The interconnected human societies and global environments are called social–ecological systems (SESs) (Ostrom, 2009), or coupled human and natural systems (CHANS) (Liu et al., 2007). In particular, an agricultural system is defined as a complex, human-managed land use system intended to provide food and services for humans (Volk and Ewert, 2011). Compared to agricultural system, a food system is a little more inclusive because it includes all aspects of activities ranging from crop production to food consumption (Ericksen, 2008). It can be easily concluded that agricultural system is the essential part in the human–environment relations, without which human can hardly live and develop in their own society. While the status of food system implies a multidimensional nature of food security, including food availability, access, stability, and utilization.

As the natural environment with biophysical processes is always changing in ways beyond human's control, the term "global change" originated from the International Geosphere–Biosphere Programme (IGBP) in the mid 1980s and was used to refer to the rapid and planetary-scale changes in the earth system. In traditional global change studies, more concern is paid to biogeophysical mechanisms and processes in the natural ecosystem, such as earth system dynamics modelling and numerical simulation, global carbon cycles in response to climate change, global land use consequences, ecosystem production structures and functions, and ecosystem feedbacks to the global environment. However, little consideration has been given to the interactive impacts of natural ecosystem and social system in the coupled systems. The understanding and addressing of both global change and its effects are not well integrated with interdisciplinary research (Reid et al., 2010).

A multi-system perspective is therefore important in addressing complex problems in the coupled systems with multiple drivers and feedbacks resulting from interconnections among interdependent components. In the environment–agriculture–food security interactions, agriculture is the basic link between natural ecosystem and human society, and the core part of food systems. Global change driver from the coupled systems greatly affects crop production and food consumption. Food systems are vulnerable to global change drivers from the atmosphere, lithosphere, hydrosphere, biosphere, and anthroposphere. Although environmental stresses contribute significantly to food insecurity, they do so

[1] World total crop production has already doubled since 1960s thanks to the "green revolution" (FAOSTAT Online).

[2] For a wide ranging discussion on current global change and food security, see the following recent special issues: *Science*, 2010, vol. 327 (Feeding the Future); *Nature*, 2010, vol. 466 (Can Science Feed the World?); *Proceedings of the National Academy of Sciences*, 2007, vol. 104 (Climate Change and Food Security) and 2010, vol. 107 (Climate Mitigation and Food Production in Tropical); *Philosophical Transactions of the Royal Society B*, 2005, vol. 360 (Food Crops in a Changing Climate) and 2010, vol. 365 (Food Security: Feeding the World in 2050).

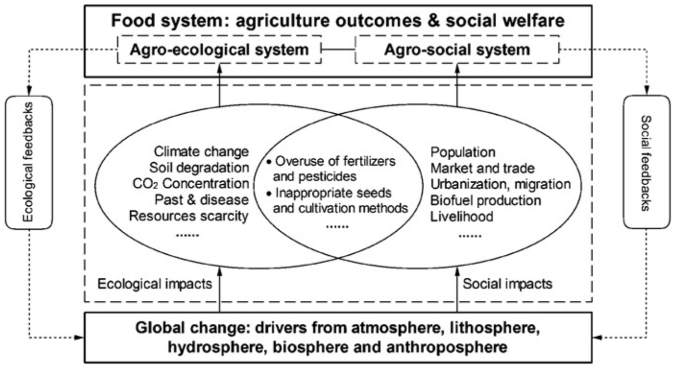

Fig. 1. Food systems and their interaction with global change.

always in combination with other drivers such as poverty, conflict, and land tenure constraints. With these, food security is challenged by the ecological impacts of global change such as substantial climate change, soil degradation, carbon dioxide concentration ([CO_2]), new patterns of pests and diseases, and a growing scarcity of land, water, and energy, in addition to severe social interruptions including population explosions, food speculation, competition from biofuel production, and urbanization and migration, as well as social-ecological impact combinations such as the overuse of fertilizers and pesticides, inappropriate seeds and cultivation methods.

Future trends such as increased demand for food with increases in incomes and populations may have consequences for global change processes. As food systems also contribute to global change, significant feedback effects exist, e.g. diet shifts and non-CO_2 greenhouse gases emissions from agriculture (Popp et al., 2010). The above summary shows that global change and food security is a complex issue with multiple determinants. A deeper understanding of earth systems, natural ecosystems, human society, agricultural systems, and food systems as agro-ecological systems and agro-social systems will help to shape a better solution to food insecurity and global change challenges (Fig. 1).

3. Global change and food security: an interdisciplinary perspective

Scientists from different disciplines have made great efforts to explain in different ways the interactions between global change and food systems (McCarl, 2010). There is a clear understanding that life sciences are important to explain how crops respond to their surroundings, while earth and environmental sciences have facilitated the researches of agricultural systems at multiple scales. Social and sustainability sciences emerged as a cross-discipline to discuss the co-evolution of human society and natural ecosystems, including the essential food systems. However, it is a pity that there are no significant interdisciplinary and collaborative works in global change and food security studies to date. Such "science behind closed doors" enables us to see only the "tip of the iceberg" in this context. In this section, we are trying to specify the focal points that each discipline should focus on and then to explain why an interdisciplinary perspective is required.

3.1. Life sciences: crop growth, yield, and productivity

Life sciences are important in exploring the mechanism through which global change affects crop growth, yield, and productivity. Biogeochemistry suggests that increasing atmospheric levels of CO_2 will change the global distribution of temperatures and rainfall, with accompanying changes in soil quality and pest and disease patterns and, consequently, crop productivity (Fleagle, 1988). Plant biology suggests that crop growth is dependent on photosynthesis associated with an accumulation of carbohydrates in source leaves, while global change drivers, such as environmental conditions, resistance to pests and diseases, agronomic practices, genetic yield potential, and interactions between these, will directly affect crop growth and yield at the field level (Gifford and Evans, 1981).

3.1.1. Crop physiology in response to different environmental constraints

If scientists can provide a clear understanding on the effects of the biogeochemical mechanism of global change on crop productivity, humans are then able to ensure or even increase crop yield in facing of global change challenges by certain genetic approaches, agronomic improvement, and water and land management. However, the mechanism of environmental constraints on crop productivity is complicated. For example, the most notable change in elevated levels of CO_2 in the atmosphere is supposed to be profitable to crop photosynthesis rates as Farquhar (1997) and Watling et al. (2000) interpreted it in the fields of paleoecology and plant physiology, respectively. However continuously elevated levels of CO_2 will not stimulate photosynthesis, biomass, or higher yields if it exceeds certain threshold levels (Leakey et al., 2006). The photosynthetic rate will accelerate with increasing growth temperatures in many species (Hikosaka et al., 2006), and C_4 plants prefer higher temperatures to accelerate photosynthesis compared with their C_3 counterparts (Berry and Bjorkman, 1980). However, even C_4 plants (e.g. maize) show only modest changes in photosynthetic rates in response to significant changes in growth temperature (Dwyer et al., 2007). Therefore, current projections of future crop yields, which assume that rising levels of CO_2 will directly enhance photosynthesis, are overly optimistic (Long et al., 2006), because they did not consider other abiotic stresses to crop reduction such as heat, water, nutrition, and ozone risk (Leakey et al., 2009; Reddy et al., 2010). Abiotic stress is not likely to occur alone, but rather simultaneously with elevated levels of CO_2 as stress combinations (Mittler and Blumwald, 2010). As many climate projections suggest that environmental conditions (abiotic factors as well as biotic factors) are likely to change concomitantly with CO_2 enrichment, more attention should be paid to stress combinations rather than to single stress impacts (Fig. 2). Although the field environment is heterogenic, a combination of approaches is needed to improve significantly the stress tolerance of crops in the field.

The fact that cold-tolerant (wheat) and cold-sensitive (rice) species favour different optimum physiological temperatures (Yamori et al., 2010) is probably determined by the difference in temperature dependence of N-use efficiency (Nagai and Makino, 2009). Elevated levels of CO_2 would trigger the closure of leaf stomata (Long et al., 2004) and boost root growth to exploit more water even from deep soil layers (Wullschleger et al., 2002), thus improving water use efficiency at the leaf and whole plant levels (DaMatta et al., 2010). However, water-stress conditions will decrease photosynthesis because of reduced CO_2 diffusion from the atmosphere to the site of carboxylation (Chaves et al., 2009). Moreover, a species-specific study explained that C_4 photosynthesis is equally or even more sensitive to water stress than C_3 (Ghannoum, 2009). Increased ozone is confirmed by both observation and projection with the elevated levels of CO_2 (Fuhrer, 2009). Although increasing ozone may slightly improve crop quality (Wang and Frei, 2011), its negative effect will decrease crop yields significantly, as suggested by long-term FACE (free-air concentration enrichment) and OTC (open-top chamber) experiments (Feng et al., 2008). Ozone risks are projected to increase dramatically in the future, thus having negative impacts on major staple crops in the long term (Fuhrer, 2009).

Climate warming is expected to alter seasonal biological phenomena (Peñuelas and Filella, 2001). Many studies have examined the crop phenology and growing season changes at regional or global levels. However, it is still difficult to explain the exact reasons

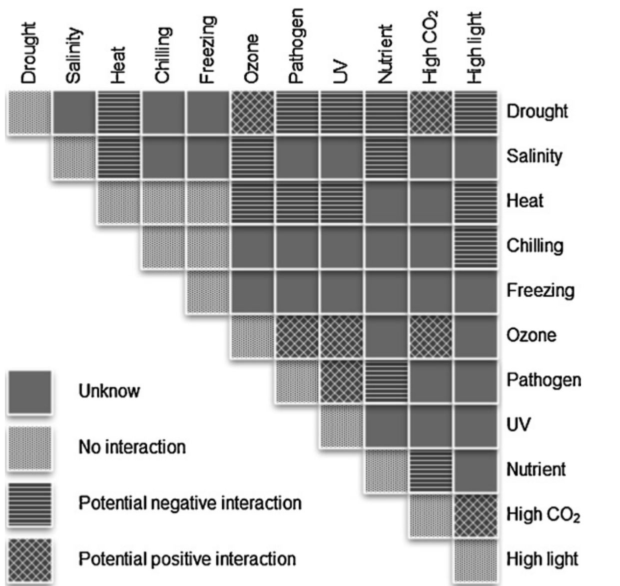

Fig. 2. The stress matrix of abiotic stress combinations. Different combinations of potential environmental stresses that can affect crops in the field are shown in the form of a matrix. The matrix is distinguished with slash line to indicate stress combinations that were studied in a range of crops and their overall effect on plant growth and yield.

The figure is modified from Mittler and Blumwald (2010).

for phenology change in response to climate change. Craufurd and Wheeler (2009) concluded that earlier crop flowering and maturity in recent decades is closely related to the warmer temperatures, but Körner and Basler (2010) stated that phenological events are not primarily controlled by temperature in temperate tree species. In addition, Yu et al. (2010) reported that warming in winter could slow the fulfilment of chilling requirements, which may delay spring phenology to those plants relying on the interplay of winter cold and spring heat. Besides, the interactions between phenology change and crop yield are still mysterious. Craufurd and Wheeler (2009) believed that warmer temperatures will probably reduce the yield of a given variety as they shorten the development stages of determinate crops. However, a study on crop phenophase by Ceglar et al. (2011) found that the selection of phenological method itself did not have a significant influence on the yield, except in years with high temperatures and limiting water conditions.

The fact is that despite many years of efforts, we are still uncertain about the mechanism through which multiple environmental constraints affect crop physiology and its yield response. This problem may raise the concern of inaccurate analysis of physiological development and will probably increase the uncertainty of impact assessment on crop yield and, consequently, the assessment of food security.

3.1.2. Crop productivity modelling

Crop yield in response to actual global change is the most concerned issue in food security assessment. Some site observation based analyses suggest that changes in primary climatic variables are the main factors affecting crop yield and productivity. By combining historical crop production and weather data, two field-level panel analyses indicated that an increase in night temperatures was found to reduce grain yield in a single farm in the Philippines (Peng et al., 2004) and in 227 farms in tropical/subtropical Asia (Welch et al., 2010); but the former study suggested that the effect of higher day temperatures on crop yield was insignificant whereas the latter found a positive effect. In the site observation based analyses in China, Tao et al. (2006) synthesized historical crop and climate data from several representative stations, indicating that there is strong correlation between the changes of climate variables and the development and production of the staple crops. Zhang et al. (2010) correlated crop yield with different climatic drivers, finding that the often-cited hypothesis of lower yields with higher temperature is not quite sure, because crop yield is intricately related to temperature, rainfall, and solar radiation. Chen et al. (2011) promoted such correlation analysis by investigating crop responses to the diurnal mean, minimum and maximum temperatures during growing season. They concluded that the daily minimum temperature was the dominant factor contributing to corn production increase in Northeast China.

Crop modelling is an effective way in predicting the performance of a given cultivar in a specified situation. Models used in simulating crop growth (hereafter referred to as crop models) include CERES, EPIC, APSIM, WOFOST, GAEZ, CropSyst, among others (Tubiello and Ewert, 2002). Early attempts of these efforts studied the relationship between selected environmental factors (e.g. CO_2, water, heat, insects and disease) and some plant processes (e.g. crop health, quality, phenophase and growing season changes). More recently, simulation works are increasingly focusing on simulating the response of crop yield and productivity in relation to global change impacts (e.g. heat stress and water deficit) (White et al., 2011). Increasing temperatures in general accelerate phenological development and increase leaf senescence, which results in a shorter growth period and yield failure. Such temperature impact was proved by a modelling work, showing that earlier phenology as a result of climate change can increase the cold damage risk of rice during reproductive growth (Hiroyuki, 2011). More specifically, average growing-season temperatures of $\pm 2\,^{\circ}$C can cause reductions in grain production of up to 50% in some wheat growing regions of Australia (Asseng et al., 2011). Some other factors such as water, genotype, and nitrogen (N) availability will limit the realization of yield potentials. By the use of a rice growth model, Yoshida et al. (2011) had examined the physiological processes that result in genotypic and N fertilization effects on yield response to elevated atmospheric [CO_2]. As crop models commonly require field calibration, Palosuo et al. (2011) examined how different models perform at the field scale, therefore to provide a typical use of models for large-scale climate change/crop production applications.

3.2. Earth and environmental sciences: crop distribution, allocation and production

Although life scientists can use fine-designed experiments and long-term site-based observation data to explain how crop will respond to different environment conditions, this kind of work is still far from enough to understand the co-evolving interconnections between crops and their environment. For instance, Peng et al. (2004) and Welch et al. (2010) showed that a temperature rise will reduce rice yield substantially in tropical/subtropical Asia. In contrast, Chen et al. (2011) affirmed that higher minimum temperatures will increase corn production in Northeast China. It is a persistent problem partly because the crop variety suitability accords to geographical distribution while environment characteristics vary spatially and temporally. As consequence, earth and environmental sciences are needed to project the current and future scenarios of climate, land use, agricultural resources, and other determinants that are important for monitoring and forecasting crop distribution, allocation and production in large geographical areas.

3.2.1. Spatially statistical relations between crop production and global change impacts

Spatial econometrics are required in assessing global change impacts on crop yield from the field to a regional or (supra-)

national scale. In China, crop productivity varies spatially with a high correlation with variations in temperature from April to October rather than with different spatial precipitation patterns (Yin et al., 2010); for example, wheat yields fall by about 3–10% with a 1 °C increase in temperature (You et al., 2009a). Moreover, climate variability influence on wheat yield exhibits different effects according to different spatial scales. In the current climate in China, the relationship between wheat yield and each of precipitation and temperature becomes weaker and stronger, respectively, with an increase in spatial scale (e.g. 0.5°, 2°, 2.5°, 4°, and 5°) (Li et al., 2010). In Africa, it is reported that climate change has strong negative impacts on staple crops; moreover, countries with the highest average yields have the largest projected yield losses (Schlenker and Lobell, 2010). Another trial-based analysis correlated the heat effects on maize yield based on historical yield trials at several locations across Africa, finding a nonlinear relationship between warming and yields. Then this result is used to up-scale to the whole continent, suggesting that roughly 65% of present maize-growing areas in Africa would experience yield losses for 1 °C of warming (Lobell et al., 2011a). In the U.S., averaged crop planting dates advanced about 10 days from 1981 to 2005 and were accompanied by a lengthening of the growth period owing to changed climatic conditions. An adoption of longer season cultivars contributes to nearly 26% of the yield increase during the corresponding time (Sacks and Kucharik, 2011). At the global scale, spatial averages based on the locations of each crop—a simple measure of growing season temperatures and precipitation—explain 30% or more of year-to-year variations in global average yields (Lobell and Field, 2007). In addition, global maize and wheat production declined by 3.8 and 5.5% in facing of climate change since 1980 (Lobell et al., 2011b). Nevertheless, some believe that the above-mentioned analyses are so superficial that they fail to provide any evidence of the underlying mechanisms. For example, the conclusion by Schlenker and Roberts (2009) that crop productivity in the USA nonlinearly and dramatically decreases at different temperature thresholds for different crop varieties was questioned by Meerburg et al. (2009), who believed that high temperatures (and also water stress) have different effects on plants at different developmental stages and are not always problematic, and that crop yields may still increase because of the advances in agronomics, breeding, and biotechnology even if exposed to high temperatures.

3.2.2. Crop model—climate model integration

In responding to this challenge, some scientists are trying to up-scale the field based crop models to demonstrate the process through which climate change impacts crops over a large area (Challinor et al., 2009), not only to examine the existing causal relationship but also to forecast the effect of future scenarios. For the crop modeller, it is necessary to define scenarios describing the future evolution of meteorological variables. The way will be simple if they focus on a field scale (e.g. by define a uniform scenario and to add these changes to the observed climate data of present, such as +10% in rainfall, +2 °C in temperature). However, it is obvious that such a method, although allowing useful sensitivity studies, relies on assumptions about future climate: it has no real physical basis, and does not preserve consistency among climate variables (Roudier et al., 2011). Therefore, an achievement in atmospheric sciences is widely welcomed by crop modelling community. General circulation models (GCMs, also known as global climate models), which are driven by scenarios of future radiative forcing, are able to generate physically consistent sets of climate variables at various spatial-temporal scale around the globe.

In the early studies, crop models were combined simplistically with GCMs (Rosenzweig and Parry, 1994). The problem is that the development of crop models was based on specific field experiments whereas GCM cannot provide such small-scale climate scenarios. How can this be solved? Easterling et al. (1998) downscaled a GCM, combined it with an EPIC model, and found that the simulation results were greatly improved. As regional climate models (RCMs) were developed to resolve small-scale atmospheric circulations for selected regions, this new method gradually became widely used with crop model combinations. Mearns et al. (1999) compared the responses of the CERES and EPIC crop models with both GCM and RCM climate change scenarios to prove the necessity of climate model downscaling in combination with crop models. Even though RCMs can provide higher resolution scenarios to reduce uncertainties, they are still inadequate to address the effects of climate change at a micro level. More crucially, when downscaling a GCM to a specific RCM, additional uncertainties will be introduced incidentally. Uncertainties also exist in different crop models. When combined with climate models, they will forecast dissimilar crop yield into the future. Most of the climate model and crop model combinations suggest that food security is threatened by climate change drastically. However, some models predict that crop yields will benefit globally from the synergy of climate change and the fertilizing effect of elevated CO_2 (Piao et al., 2010).

3.2.3. Agricultural land use change

At a landscape scale, agricultural land systems sustain crop production, enabling crops to be harvested in large enough amounts to satisfy human need. In comparing with the crop productivity in a field, crop distribution and allocation on the landscape and its dynamics are also important for food production. "Land change science" has emerged as a discipline seeks to understand the land system in the coupled human and natural systems. The dynamics, causes, impacts, and consequences of agricultural land use change have been addressed as an important component of land change science (Turner et al., 2007). Theories, concepts, tools, techniques, models, and applications of agricultural land use change are valuable for global change and food security debate.

Farmland refers to the land that is suited to or used for crops, which is indicated to be a foundation for agriculture. According to the FAOSTAT, farmlands cover 1.53 billion hectares (about 12% of Earth's ice-free land), while pastures cover another 3.38 billion hectares (about 26% of Earth's ice-free land). In total, agriculture occupies about 38% of Earth's terrestrial surface—the largest use of land on the planet (Foley et al., 2011). However, its amount and distribution is changing over the temporal and spatial dimensions. In some recent decades, the world's farmland has expanded, and contributed to a ~12% increase in grain production worldwide (Foley et al., 2005); although this has been questioned because much evidence suggests that the world total farmland area has not increased recently (Ramankutty et al., 2008; Rudel et al., 2009). In fact, significant farmland expansion took place in the tropics through deforestation, posing hazard to biodiversity, carbon storage and important environmental services (Foley et al., 2011). In contrast, in some regions, farmland has been substantially converted to other land use types, posing great potential risk to food security. For instance, historical inventory data and remotely sensed land-cover data show that the rate and extent of farmland abandonment has greatly increased since the 1950s, which mostly exist in some regions of North America and Central and Eastern Europe (Cramer et al., 2008). In China, because of its fast urbanization and other land use policies (e.g. Grain for Green Project), the amount of farmland has decreased in recent years at an astonishingly high rate; for example, during 1996–2008, the amount of cultivated land decreased from ~130 Mha to ~122 Mha according to the National Bureau of Statistics of China. Although there was little change in the sowing area, such landscape conversion trends will make it increasingly difficult for China to feed its huge population.

Crop pattern refers to the temporal-spatial combination of diverse crop allocation, crop distribution, annual multi-cropping, land fallow, and other planting methods in a specific region (Tang et al., 2010a). Although we commonly characterize the land surface by distinguishing different land use and land cover types, crop pattern may frequently and drastically change without any change in land cover level (Verburg et al., 2009). In consequence, crop pattern dynamics contributes to great fluctuations in food production, but they are not always easily observable, hence making many difficulties for analysis. For example, the global crop allocation is generally 62% for human food, versus 35% for animal feed, and 3% for bioenergy, seed and other industrial products. There are striking disparities that developing economies primarily grow crops for human consumption, whereas those developed economies are now producing more and more crops for other uses (Foley et al., 2011).

Land change science in the global change/food security debate is required fundamentally to describe the place, quantities, rates, and drivers of farmland transition. For example, a typical study from Baumann et al. (2011) explained that about 6600 km^2 (30%) of the farmland used during socialism was abandoned in Western Ukraine due to regime shifts associated with other determinants. Far more important, though, is that an interdisciplinary land use perspective could provide a productive way to explore the spatial patterns of land use and its possible consequences to crop production at different scales both in present and future. Certainly, landscape conversion contributes greatly to the inventory of farmland acreage, however, crop system alteration and agricultural land management at the farm-level affect soil quality, water resources, and food production to a great extent. Land use practices therefore will benefit food production through agricultural intensification. With regard to the world grain harvests in the past few decades, appropriate land use decisions and management practices, such as high-yielding cultivation, chemical fertilizers and pesticides, and mechanization and irrigation, contribute more to food production than does landscape conversion (Foley et al., 2005; Matson et al., 1997). The significant influence of land availability, degree of urbanization, technology extension, and government policy on food production promoted agricultural intensification across the globe. However, intensive use of physical inputs and increasing intensity of farming systems will degrade the environment. Consequences of soil degradation, water scarcity, and severe pollution were actually happened in most crop yield-increasing regions in China (You et al., 2011). Food production must grow substantially while, at the same time, agriculture's environmental footprint must shrink dramatically (Foley et al., 2011).

3.2.4. Agroclimate resources and crop yield gap

The distribution of agroclimate resources determines the global crop distribution and yield patterns, to which we commonly known as maximal climatic potential yields (Lobell et al., 2009). Under the current global climate change, the global crop yield patterns have been modified substantially. A national-wide analysis has discussed the possible effects of climate warming on the north limits of cropping systems in China in the recent three decades. Some conclusions have been made as first, the north limits of cropping systems in China expanded northward or northwestward significantly due to the rising temperatures. Second, such expansion will probably increase food production in China by shifting some single-cropping areas to double-cropping in the North, and shifting some double-cropping areas to triple-cropping in the South (Yang et al., 2011). Although the assessment gives an optimistic outlook on future food production in China, it is oversimplified by the lack of linkage of agroclimate resources to actual farmland distribution on the landscape and crop conditions in the field. Actual cropping system (e.g. multiple cropping) response to climate change should better be verified by remotely sensed images, rather than roughly judged by agricultural meteorology method (Tang et al., 2011). However, it would be more productive when combining the two methods together (Li et al., 2012).

In reality, there are a lot of underperforming landscapes around the world, where yields are currently below average. Crop yield gap is therefore defined as the difference between crop yields observed at any given location and the crop's potential yield at the same location with given current agricultural practices and technologies. Recent analyses have found that, based on global current crop distribution, actual grain yield in some regions is already approximating its maximum potential yields while other regions show large yield gaps. The most significant yield gaps distributed at many parts of Africa, Latin America, Southeast Asia, and Eastern Europe (Licker et al., 2010; Neumann et al., 2010; Yu et al., 2011). Although climate change is always regarded as a key driver for determining the global crop yield patterns, contributions from irrigation, accessibility, market influence, agricultural labour, among others, are significantly to increase grain production efficiencies, thus narrowing the yield gaps (Neumann et al., 2010). Closing crop yield gap requires intensive land management practices. However, as discussed above, intensification activities could adversely affect ecosystem goods and services. It is worthwhile to note that intensification factors have different effect on grain production efficiencies, and are strongly scale dependent. Factors with great importance at global scale are not necessarily significantly at regional scale (Neumann et al., 2010). Therefore, the issue of crop yield gap should be addressed with a region-specific perspective rather than at global scale overview. Region-specific analysis is also important in clarifying the trade-offs between agricultural intensification and environment degradation, despite that a sustainable manner for both food and ecological systems still remains in question.

3.3. Social and sustainability sciences: food system vulnerability and adaptations

The most serious problem that challenges life and environmental scientists is the so-called "dumb farm scenario" that omits the range of adaptations that farmers customarily make in response to changing economic and environmental conditions (Mendelsohn et al., 1994). Though some models make explicit attempts to model farmers' adaptation, it is quite difficult and not satisfactory simply because it is hard to predict what the future farming system would look like under usually long-time global change scenarios. Therefore, profound knowledge in social and sustainability science is required in global change and food security researches for evaluating the food system's vulnerability within a region or country, and to examine the value and nature of adaptations and mitigations made through economic activities or policy design.

3.3.1. Adaptation

According to the Intergovernmental Panel on Climate Change (IPCC), adaptation means adjustment in natural or human systems in response to actual or expected change or their effects, which moderates harm or exploits beneficial opportunities. The term involves two main aspects: capacity and decision. In contrast to natural ecosystems, the response of food systems involves more human dimension adaptation, such as genetic approaches, agronomic improvement, and water and land management in food system capacity building. Plant breeding and molecular genetically modified crops have achieved high yields (Fedoroff, 2010). By carrying out potential-yield trials based on the performance of leading common wheat genotypes in separate farm plots across China, Zhou et al. (2007) concluded that wheat breeding in China in the last 4–5 decades enhanced grain yields significantly while disease resistance and grain quality also improved. Although the warming trend most likely had a negative impact on crop production, the adoption of new crop varieties was able to compensate for such a negative impact (Liu et al., 2010). The terms of changing timing of cultivation and selecting other crop species and cultivars are also the main farming adaptation strategy in Europe (Olesen et al., 2011). Technologies such as irrigation and mechanization will increase agricultural productivity, but the effect may differ in each specific case when economic and environmental costs are considered. For example, in some studies, drip irrigation has been reported to increase yields gains and save water and associated fertilizer, pesticide, and labour inputs. However, the use of this conventional technology has been limited in Africa because of a lack of access to water and other agronomic and financial supports (Burney et al., 2010). Apart from capacity building, adaptation can also be achieved by implementing adaptation decisions (Adger et al., 2005). Although advanced technology and high-yielding cultivars are crucial to increasing yields, the adoption of a new variety is a complicated process. There are important differences across crops and regions regarding the date at which significant adoption of new varieties first occurred and in the subsequent growth in rates of the adoption of new varieties. For instance, large numbers of new varieties were released in Sub-Saharan Africa in the 1960s and 1970s, but there was little adoption by farmers (Evenson and Gollin, 2003).

Humans can prioritize their adaptation by projecting into the future. An analysis based on statistical crop models and climate projections indicated that South Asia and Southern Africa, two of the world's 12 food-insecure regions, will probably suffer the most from food insecurity by 2030 (Lobell et al., 2008). In this case, switching from highly impacted to less impacted crops may be one viable adaptation option. Challinor (2009) made a similar projection involving genotypic adaptation, examining what biophysical properties are likely to be required of crop varieties grown under future climates. However, this method does not result in specific recommendations on crop variety options, because of the non-linear interactions that may exist between genotype and the environment. Adaptation in food systems is complicated because humans always try to avoid harm and to do good, and they do not separate the adaptation decisions from actions triggered by other social or economic events, and such behaviour will magnify the uncertainties of the impact of global change. For example, with regard to the recent expansion of rice production in northeast China, some scientists believe that about 40–70% of this change is the result of human economic behaviour rather than adaptation to climate change. Rice production is more profitable than maize even though the environment condition in some of the areas are not suitable for rice production (Wang et al., 2005).

Who makes adaptation decisions? The attempts in food systems to adopt new ideas as well as to adapt to global change can be conducted at many levels: individually, socially, and governmentally (Yu et al., 2012). The assessment of adaptation strategies, regardless of whether they relate to capacity building or decision making, should be considered across various levels to maximize benefits for the whole of human society. For instance, farmers can respond creatively and adaptively to global change; however, it must be consistent with common interests in a society that provides institutional and macroeconomic conditions that support and facilitate adaptation. Conversely, policy can hardly make sense if it does not satisfy individual benefits. The judgements of the success of human adaptation to climate change should be based on effectiveness, efficiency, equity, and legitimacy in terms of the sustainability of development pathways into an uncertain future (Adger et al., 2005). As sustainable options for agricultural systems are needed to be adapted by individual farmers, the possibility and effectiveness of adaptation should be examined by an upscaling method from farm-level to regional level (Reganold et al., 2011; Righi et al., 2011).

3.3.2. Vulnerability

Vulnerability is a state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt (Adger, 2006). This poses three critical questions related to food systems. First, is the change severe enough to cause damage? Second, is the adaptive capacity strong enough to cope with the hazard? Third, can we develop an appropriate adaptive strategy to minimize such a hazard? The answers all relate to one key word: unbalanced; which means that the degree of vulnerability is different in specific areas across the world; either regarding the hazard severity or the adaptive capacity. Generally; vulnerability in developed economies is less than in developing economies; and hunger is always accompanied by poverty. For example; dryland Sub-Saharan Africa and Asia may face more stresses from environmental conditions; and people in such areas who suffer from poverty are less likely to improve their adaptive capacity through technology or financial support. Vulnerability of the food system to global change is not only a natural hazard but also a social and economic problem (Lotze-Campen and Schellnhuber, 2009). Temporary food shortages can be fixed by markets and trade; however; this occurs only when economic capability; market function; and trade policy are all in good condition (von Braun, 2009). Otherwise; food shortages will cause unexpected outcomes on smallholders and subsistence agriculture; such as migration; social disturbances; or even the outbreak of war (Burke et al., 2010).

With regards to adaptation, vulnerability often emerges and is associated with uncertainty and risk. Vulnerability exists when there is uncertainty about the future outcomes of ongoing processes or about the occurrence of future events. Certainty will lessen risk, as it allows ex ante choices and preparation against the negative impacts of future events. Climate change projections suggest that global temperatures will continue rising and extreme weather events will increase in frequency and intensity, which requires humans to improve their adaptive capacity in food production. However, projections of future climate change suffer from the uncertainties that exist in climate modelling as well as crop modelling methodologies (Müller, 2011), including uncertainties in the setting of climate forcing conditions and the constructing of socioeconomic scenarios, and they reflect ignorance of many physical, biological, and socioeconomic processes. In previous global change studies, little attention has been given to the sensitivity of management decisions to uncertainties in environmental prediction measures, making it difficult for planners to make appropriate decisions on adaptation.

3.4. The interdisciplinary perspective

Knowledge about the effect of the mechanism of global change drivers on crops is the basic foundation for the follow-up research in food security, For example, climate change induced variations significantly affect not only crop growth and yield but also crop prices and food markets (Furuya and Kobayashi, 2009). However, this type of knowledge is missing in both specific-discipline and cross-discipline fields.

Previous studies considered only a single biophysical factor related to crop physiology, and rarely considered their combined impacts on photosynthesis, crop health, yield, and quality. Except the commonly discussed climate change impact on crop production, social driving force is always ignored in food security analysis, which includes the considerable transforming role of the interacting driving forces of population growth, income growth, policy, urbanization, and globalization on food production, markets, and consumption. Land use activities, in particular the pressure on land for different services (e.g. food or non-food commodities, livelihood, biodiversity, and carbon sink), are likely to be the most critical of all human-induced global change driving forces (Turner et al., 2007). Moreover, their impacts seem to be magnified nowadays by involving more market and policy factors, social feedbacks, as well as different human interests in the coupled human and natural systems. Considering the expansion of biofuel crops for example, the emergence of agro-energy has altered land use dynamics, albeit not yet significantly (Rathmann et al., 2010). Although the biofuel crop is favoured by farmers as an additional source of income and encouraged by governments as a powerful substitute for fossil fuels, it has adverse impacts on food supply, market prices, and consequently food security as its competes with food production for land and water resources. Moreover, substituting biofuels for gasoline will affect the global carbon cycle because land use change involving converting forests and grasslands into new croplands will increase greenhouse gas emissions, which will offset the carbon savings from the substitution away from fossil fuels (Lapola et al., 2010).

Even if we succeed in integrating the multiple mechanism of climate change, land use change, and human society driving forces into the existing research, the expertise of specific-discipline should be exchanged for collaborative researches. For example, plant scientists are subjected to a mixture of experimental and observational studies and may find that some experiments are excellent in explaining how crop growth is affected by changed environmental conditions. However, their results cannot be introduced into crop models to forecast yield because the scientists who carried out such experiments do not understand crop growth simulation. To modellers on the other hand, Rötter et al. (2011) sharply pointed out that many of the current crop models are badly out of date that they do not incorporate the latest knowledge about how crops respond to a changing climate and may not properly represent modern crop varieties and management practices. Moreover, crop modellers may also have difficulty in coupling an upscaled crop simulation model with a spatial climate model as there is no superior empirical or experimental data available for model parameterization. Therefore they often fail to quantify the uncertainty of their models—a problem that can promote mistrust in model results and make it difficult for policymakers to act on the information. Furthermore, economists often use statistical data to predict the equilibrium of food supply and demand in the future without paying sufficient attention to biogeophysical drivers that may affect crop production, thus making the prediction unreliable.

Global change impacts and responses need to be characterised in context (Rosenzweig and Wilbanks, 2010). There is an urgent need for a tight interdisciplinary effort involving life science, earth and environmental science, and social and sustainability science to better understand the issues of global change and food security, not only in comprehensively incorporating multiple biogeophysical and socioeconomic factors into global change and food security analysis, but also in collaboratively exchanging the latest knowledge updated in various disciplines.

4. Global change and food security: a cross-scale perspective

The complexity of global change and food system interactions mentioned above requires a multi-system and interdisciplinary perspective so as to cover all the scientific issues in this field and to better describe their interactions. To specify, we propose a cross-scale framework for carrying out specific researches at different levels (field, regional, and global) and different disciplines (life science, earth and environmental science, and social and sustainability science) as shown in Fig. 3. Each level has its own priority and major scientific issues, which are tightly linked with different disciplines (yet not necessarily one to one correspondence). The final objective is to provide an integrated platform for better describing the dynamic relationships between global change and food systems across the world, thus helping to achieve the global target of food security. Additionally, domestic/international cooperation among research institutes and research programmes is equally as important as interdisciplinary integration.

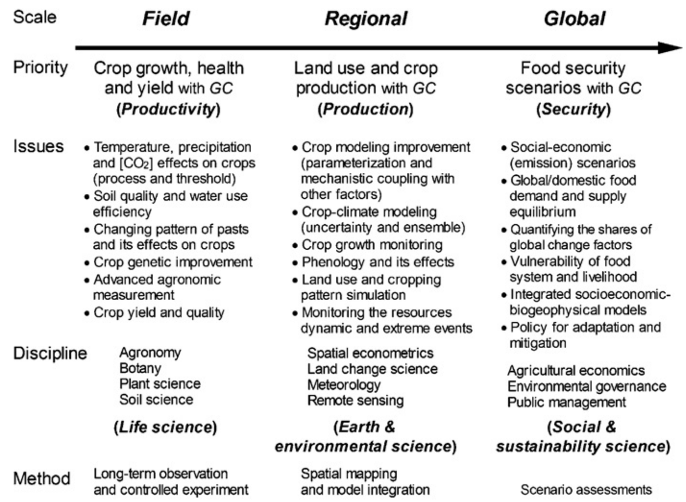

Fig. 3. The conceptual framework for global change (GC) and food security studies.

4.1. Observation-based or experiment-based field level research: actual crop responses

The main objective of field level research is to understand the mechanism through which global change will affect crop growth, crop health, and crop yield. The primary climatic variables such as temperature, precipitation, and CO_2 are the main determinants of crop growth, and should be examined by long-term observation and controlled experiments, which will finally improve our understanding of how crops respond to the changing environment. After that, the results of observation and experiments should be explained by quantitative analysis, such as crop yield modelling. There is a strong controversy between process-based and statistical-based crop models. Rötter et al. (2011) believed that process-based crop models (briefly known as crop models), which apply the understanding of physical and biological processes, such as how given crops respond to increased CO_2, reduced water supply, warmer growing seasons or changed crop management, will provide a distinct advantage in forecasting how farm-level productivity may change. In contrast, Lobell and Burke (2010) argued that process-based models require extensive input data on cultivar, management, and soil conditions, and need careful field-scale calibration on a large numbers of uncertain parameters, while statistical-based models are much more straightforward. Which one is better? We suggest that those complicated process-based models are good at simulating crop response to synthetic climate conditions, especially in forecasting into the future, while the straightforward statistical-based models are effective in analysing the contribution of each climatic variable's impact on crop yield, thereby determining the most important factor that induces food system vulnerability.

Still, several issues are being debated for crop yield modelling. For statistical analysts, they have to explore the most significant and scientific indicators that can best explain crop yield change in relation to climate change (e.g. growing degree days, daily minimum and maximum temperatures, effective accumulated temperature, gross precipitation, growing days precipitation, precipitation at different growth period), because a different indicator means a dissimilar effect on crops and their yield. In addition, some elucidation of nonlinear temperature effects on crop yield is worthy of consideration (Lobell et al., 2011a; Schlenker and Roberts, 2009). Even though such an observation cannot fully explain the comprehensive set of factors that influence crop growth and yield, it can provide us with an intuitive insight into crop response to changing climate conditions. For crop modellers, though they have recalibrated their model over time, they urgently need to update such work to reflect new research in crop physiology, agronomy and soil science. For example, the current CO_2 fertilization factors are overoptimistic and can be offset by a series of negative processes; consequently, the parameterizations in the current prevailing crop models may be outdated (Long et al., 2006). The conclusion about nonlinear temperature effects may contribute to model improvement. Moreover, an ensemble approach is required to reduce uncertainty among various crop models. As there is clearly no best model, determining multi-model averages is a promising practice that can help to better replicate observed results (Palosuo et al., 2011). Nevertheless, if the numerous results of process-based models as well as statistical-based models can be integrated into meta-analysis, the conclusions will be robustly scientific (Müller, 2011; Roudier et al., 2011).

Attention should also be paid to biotic factors other than climatic variables. Soil degradation and pests/diseases will cause crop failure in the field. Moreover, they have space-time connectivity to other factors. For example, climate change will alter the temporal-spatial pattern of pests and diseases, which will have unpredictable influences on crops (Ghini et al., 2008). Likewise, the same thing will happen to soil quality and water availability (Lal, 2009). Therefore, field level specific studies are required to investigate such impacts and make it possible to develop mechanistic linkages to other factors across both of time and space dimensions.

The “green revolution” has enabled impressive agricultural productivity increases because of the introduction of high-yielding varieties of wheat and rice, in combination with the extensive application of fertilizer and pesticides, mechanization, and irrigation. However, the original objective of the “green revolution” was not to design solutions to cope with challenges brought about by global change. Climate change is projected to affect agricultural production, yet analyses of impacts on in situ conservation of crop genetic diversity and farmers who conserve it have been absent. The evolutionary response of landraces and genetic resources conservation will be crucial in adapting to the imminent threats of climate change, which should be addressed using an interdisciplinary approach and collaborative international cooperation (Burke et al., 2009). Moreover, future agronomic research should not be confined to yield improvement but should also consider stress tolerance and genetic diversity.

4.2. Spatial analysis-based regional or (supra-) national level research: linking crop with its environment

The main objective of regional level research is to link crop performance in the field to its geographic environment, including farmland and crop distribution, crop allocation and agricultural intensification. At the regional level, spatially explicit analyses are the key technology for simulating the effects of global change on crop production, ranging from climate scenarios to land use, and from crop systems to the geographic distributions of pathogens. Tasks at this stage are to re-examine the results of field studies using large scale applications and, at the same time, provide biogeophysical as well as socioeconomic linkages using various spatially explicit modelling techniques, including climate, land use, and crop growth scenarios to upscale the outcomes of field studies to regional studies.

When upscaling the crop yield simulation to regional application, debate is triggered again between process-based and statistical-based crop models. Statistical models have a slight advantage, because other than purely field based time series analysis, statistical methods can also be used in studying variations in space (cross-section methods) and even variations both in time and space (panel methods) (Lobell and Burke, 2010). When the statistical models are applied to large areas (e.g. at a continental scale), environmental zoning methods will be helpful in characterizing agroclimatic zones for a more general assessment (Trnka et al., 2011). Data aggregation can facilitate crop model upscaling (van Bussel et al., 2011), while another possible and effective way is assimilation of remotely sensed data into crop model parameterization (Fang et al., 2008). Nevertheless, the tougher question in future prediction lies in how to update CO_2 fertilization and how to incorporate pest and disease impacts in combination with climate projections. Uncertainties in climate–crop modelling will be present in the first place, in company with the selection on climate projections. GCM is feasible when dealing with areas without complex terrain. Anwar et al. (2007) linked CCAM (GCM) with CropSyst, whereas Alcamo et al. (2007) linked ECHAM and HadCM3 (GCMs) with GAEZ in Australia and Russia, respectively. When considering the monsoon climatology in China, a combination of a crop model with an RCM will improve simulation accuracy. Therefore, PRECIS (RCM) was combined with CERES (Lin et al., 2005), and RegCM3 (RCM) was combined with EPIC (Chavas et al., 2009) to analyse the impact of climate change on crop productivity in China. A possible solution to such a problem is a multi-model ensemble for providing climate scenarios, e.g. using a probabilistic method to develop most likely climate scenarios generated from multiple GCMs will reduce uncertainty (Tao et al., 2008), and to further incorporate climate change with socioeconomic drivers (Xiong et al., 2010). The use of ensemble approaches is also effective in minimizing uncertainties in crop modelling (Fig. 4). For example, Challinor et al. (2009) used the output from climate models, combining the benefits of process-based crop models such as the DSSAT suite with the benefits of statistical models in order to simulate yields over large areas. Such a method is named as general large-area model for annual crops (GLAM), which had been applied to many regions, including Africa, India, and China (Challinor et al., 2010).

When incorporating the geo-distribution of crop pests and diseases, soil content dynamics and irrigation availability into regional crop models, the issue will become more complicated. A spatial biogeochemical simulation shows that the loss rate of organic soil carbon is different according to the crop pattern type (as maize > paddy > winter wheat and corn rotation) (Tang et al., 2010b), while a statistical meta-analysis suggests that biochar application to soils will increase crop productivity by 10% (Jeffery et al., 2011). However, the dynamics of soil carbon change are not well incorporated into crop models, which hinders improvement in crop yield estimation. Globally, about 92% human water use is consumed for agriculture, among which grain products gives the largest contribution (27%) (Hoekstra and Mekonnen, 2012). A lot of increased crop production can only be obtained with sufficient water availability for irrigation. However, the spatial-temporal patterns cross-scales for irrigation are not so much clear that adding more uncertainties on regional crop modelling. The distribution of crop pathogens has been constrained by cold winters and geographic isolation. Therefore, the warming trend will cause more crucial diseases and insect pest problems in high-latitude areas (Roos et al., 2011). Additionally, the homogenization of the agricultural landscape could facilitate widespread disease and pest outbreaks (Margosian et al., 2009). The traditional modelling of pests and diseases combines experimental data and

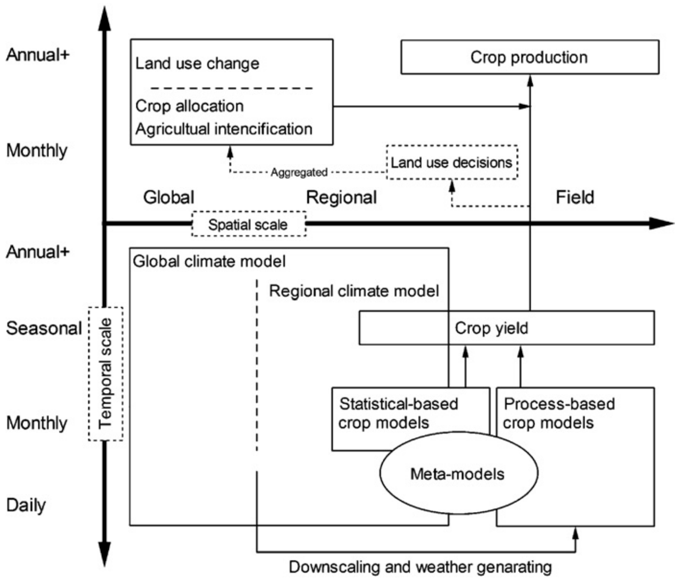

Fig. 4. General representation of across-scale model integrations. In the bottom part of the figure, climate models are used to generate weather conditions for crop yield forecasting at multi-temporal-spatial scales. The advantages multiple outputs of climate model as well as various process-based and statistical-based crop models are supposed to be integrated together for ensemble analysis. In the upper part, crop yield estimation is used to drive the decision model for land use change modelling. Finally, crop production can be estimated by combining crop acreage and crop yield together.
The bottom part of the figure is modified from Challinor et al. (2009).

population dynamics modelling (Estay et al., 2009), or combines geospatial data and pest seasonal phenology information (Beddow et al., 2010). Butterworth et al. (2010) combines the upscaled-crop model and weather-based epidemiological models to predict the crop–disease–climate interactions in different areas of Britain, finding that climate change will cause different impact on crops in the presence of pathogens. It is urgent that the crop–pathogen interaction be better integrated into the climate change/food security debate (Gregory et al., 2009). To study the effects of climate change on crop diseases, we should pay attention not only to the climate change impacts themselves but also to disease complexes and pathogen adaptation. Moreover, studies on pest outbreaks and disease epidemics and their space–time distribution should be enhanced in relation to future climate scenarios.

Crop growth monitoring by the use of a remotely sensed data provides crop area, crop phenophase, and soil moisture information cross a large region (Bridhikitti and Overcamp, 2012; Wu et al., 2010). When combining this information with spatially explicit models, analysts are able to make objective, timely, and quantitative yield forecasts on a regional scale. The CGMS (Crop Growth Monitoring System)[3] developed by MARS (EU programme, Monitoring Agriculture with Remote Sensing) is an achievement in realizing such an objective. CGMS monitors crop development driven by meteorological conditions modified by soil characteristics and crop parameters. It is worth considering this mechanistic approach when describing a crop cycle in combination with weather monitoring, phenology stage, crop simulation, and yield forecasting. Attention also should be paid to resource and extreme events monitoring. Variations in temporal-spatial distribution affect crop yield to a great extent, and often they have not been given adequate consideration in previous studies.

Land cover mapping is a basic tool used for food security assessments, as it provides information on shape, area, and spatial location for farmland. However, current land cover data sets were developed for numerous purposes at different spatial scales, originating from plentiful sources and inventory techniques, which make applications difficult (Verburg et al., 2011a). An accuracy assessment for four 1 km global land cover datasets on China's farmland suggested that it is necessary to choose the most appropriate data for specific purposes (Wu et al., 2008) (e.g. regional crop production estimation and farmland management). Land use mapping, along with land cover mapping, is equally important to global change/food security studies. Land use mapping is more inclusive as it can either be physical aspect (e.g. crop allocation) or socioeconomic aspects (e.g. market accessibility). You et al. (2009a,b) developed a Spatial Production Allocation Model (SPAM) for generating plausible geographic crop distribution maps by the use of spatially disaggregated data fusion and cross-entropy approach. Foley et al. (2011) applied the non-spatial crop allocation data to the spatial farmland maps for extracting the crop area as fraction of farmland at a global scale. Monfreda et al. (2008) examined data sets presenting information about agricultural land use practices such as crop selection, yield, and fertilizer use. Similarly, Temme and Verburg (2011) made a spatial map of agricultural intensity for further analyses. MIRCA2000 (Portmann et al., 2010) provided monthly data on irrigated and rainfed crop areas for 26 major crop classes for each month within the year. Sacks et al. (2010) provided data sets containing information on dominant crop patterns and full details of planting and harvesting periods in each region. Neumann et al. (2011) mapped an overall pattern of irrigated croplands globally. Verburg et al. (2011b) creatively presented a gridded data depicting market influence on global agriculture and other land use systems. These prevailing examples were mostly focusing on global scale overviews. However, small-scale maps with high spatial resolution are more welcomed for a specific application, as they can be easily linked with crop conditions in the field for integrated assessment on regional food production. Moreover, the integration of climate, land use and crop growth at the regional level requires careful selection of biogeophysical/socioeconomic linkages between factors, and a reduction of uncertainty by data/model validation.

Spatially explicit land change models have been used to represent land use change and its possible developments across regional level to continental level (Schaldach et al., 2011; Verburg et al., 2002). Although we commonly simulate the landscape by dominant land cover types, landscapes in the real world are mosaics with multiple functions, in respect of biodiversity, carbon, soil, water, ecosystem services, and food production. Accurate land use simulations provide a better understanding of land use change, not only land conversion, but also crop pattern dynamics and food production at the regional level. All processes ranging from expansion/abandonment of agricultural area to intensification of land use systems happen at same time depending on land use, environmental, socioeconomic and governance conditions. Therefore, traditional spatially explicit land change modelling is facing challenges in transforming from "land cover" to "land systems", which will not only facilitate the analysis on trade-offs between food production and environment sustainability, but will also benefit the identification of underperforming farmlands across the world to close the yield gaps. The innovation on land change modelling also requires an integration between "landscape conversion" and "land use decisions" to better represent household adaptation to global change based on land use behaviour measurement. Landscape conversion is always detected at a macro-level, while land use decisions, ranging from farming strategies (sow or fallow) to crop choices (food crop or biofuel plant) to management decisions (whether to invest in irrigation, fertilizers, and pesticides) mainly

[3] MARS-CGMS Online: http://mars.jrc.it/mars/About-us/AGRI4CAST/Crop-yield-forecast/The-Crop-Growth-Monitoring-System-CGMS.

happens at farm levels. Land users (i.e. farmers or households) make their land use decisions based on complicated factors including climate change, market, policy, and individual behaviours will greatly affect crop production at the regional level (Wu et al., 2007). In particular, land use decisions made by individual land users were according to an understanding of their internal willingness or ability associated with the external conditions of the environment (e.g. global change impacts on food systems) (Valbuena et al., 2010). Therefore, land use decision is a typical combination of environmental change and human adaptation, which can also be regarded as the most critical linkage between the field level crop condition and the regional level crop production. Such choice-making processes should be incorporated into decision models, and aggregated at an upper level for regional land change models (Fig. 4). Land change modellers therefore need to integrate these farm-level land use activities into traditional land change modelling measurements. A possible solution is "agent-based modelling", to integrate "top-down" method with a "bottom-up" measurement, and turn "factors" into "actors" and change "pixels" to "agents". Such integration not only benefits the land change modelling community, but also facilitates the analyses on global change adaptation, from an individual level decision-making perspective (Yu et al., 2012).

4.3. Scenario assessments-based global level research: food security and adaptation strategies

"Global level" here does not just mean world-wide, but also means comprehensive integration. Researches at different scales and in different disciplines are supposed to be well integrated for developing credible scenarios. The goal of scenario-based assessment is not to predict the future but rather to better understand uncertainties in order to make adaptive decisions.

In the global change context, uncertainties exist in areas from human society to natural ecosystems to coupled systems. Previous global scale scenario studies include the Special Report on Emission Scenarios (SRES), the Global Environment Outlook (GEO), and the Millennium Ecosystem Assessment (MA), which encompass interactions among socioeconomic growth, population, land use, emissions, climate, and environment (Moss et al., 2010; van Vuuren et al., 2010). It is commonly accepted that the effects of climate change are strongly influenced by socioeconomic change, such as emission and land use change; and for assessment of climate change impacts, it is important to separate the different components such as socioeconomic contributions and "net" impacts attributable to climate change. Therefore, the socioeconomic scenarios are fundamental for climate projection as well as impact assessment. In the last two decades, IPCC scenarios and processes (SA90, IS92, and SRES) have been broadly used in global change studies, especially the SRES. However, as argued by Pielke et al. (2008), the impact of such productive scenarios on technological advance may be greater than we think, making the SRES scenarios outdated. Moss et al. (2010) debated whether new scenarios and a new process for selecting and using them are needed, and they concluded that nearly a decade of new economic data, information about emerging technologies, and observations of environmental factors such as land use and land cover change should be reflected in new scenarios. Therefore, more reliable socioeconomic scenarios should be developed urgently through collaborative studies to facilitate follow-up studies using the framework of global change and food security.

The complexity of food systems makes them unpredictable in both the present and the future. Thus, scenario analysis is important in conjunction with various models to explore plausible future outcomes (Reilly and Willenbockel, 2010), which are referred by policymakers as IAV analysis (vulnerabilities, impacts, and adaptation) (Rosenzweig and Wilbanks, 2010). Ye and van Ranst (2009) developed a future food production scenario for China, by combining decreasing amounts of farmland with soil degradation, it indicates that the present-day production capacity will not sustain the long-term needs of its growing population. The scenario makes sense for policymakers that current land management practices are not sustainable, at least for food security. Traditional food system models present the equilibrium of food production, consumption, and trade, or the equilibrium of food demand and supply, such as the Global Trade Analysis Project (GTAP, Center for Global Trade Analysis), International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT, International Food Policy Research Institute), and the World Food Model (FAO), which are valuable tools for assessing food security at the global level. However, such models lack linkages to biogeophysical processes including crop growth, land use, and climate change. Because of the multiple socioeconomic and biophysical factors affecting food systems and hence food security, the capacity to adapt food systems to reduce their vulnerability to global change is not uniform (Gregory et al., 2005). Some of the partial equilibrium models mentioned above, such as IMPACT, incorporate climate change drivers to demonstrate the possible negative effects of increased climate variability on food production (Nelson et al., 2010). However, this considers the climate variables as a special kind of resource endowment rather than trying to explain crop failure from the perspective of crop physiology. For the IAV community, Integrated Assessment Models (IAMs) should be developed at more aggregated scales. Especially, the shares of different global change factors (e.g. climate change, policy intervention) contribute to food security are supposed to be quantified. Regarding the considerable progress in crop growth modelling and crop pattern modelling, it is innovative and possible to integrate socioeconomic and biogeophysical factors together to generate more comprehensive scenarios for future food security assessment (Wu et al., 2011). Scenario analysis in vulnerability, policy adaptation, and mitigation (e.g. shifting diets and reducing waste) will yield valuable insights into capacity building, poverty reduction, and adaptation prioritizing, and consequently food security.

5. Conclusions

As an old Chinese saying goes "food is the first necessity of the people", indeed, food producing is the single largest human impact on our finite planet. However, a strange situation is that, despite tremendous gains in "green revolution", which enables our planet with sufficient food for all, it still cannot prevent approximately a billion people go hungry worldwide, while another billion overconsumed, increasing risks from chronic diseases along with social disturbances.

What makes this difficulty? Lobell et al. (2011a) suggests that climate change made crop yield losses, especially in the heat-sensitive Sub-Saharan Africa. Foley et al. (2011) implies that although common crop production increased by 47% between 1985 and 2005, however, the production contribution from different crops is sharply disparate: food crops only have a 34% increase in yields per hectare (much less than oil crops), with decreased in harvested area by 3.6%. Moreover, Rosset (2011) explains that food crops were mostly allocated in food-secured developed regions, while some of the food-insecured developing areas would probably use their limited land to plat high-profit economic crops for trading cheaper foods, according to the "economic law of comparative advantage". In the presence of food speculation, such a way will exacerbate rather than alleviate hunger.

Clearly, explanations from different standpoints demonstrate that global change/food security is really a complicated issue that requires a multi-dimensional perspective. In this paper therefore, we clarified this multi-dimensionality by proposing an integrated framework for future global change and food security researches. Firstly, the interaction of global change and food security should be discussed in a multi-system context. Both the biophysical and socioeconomic aspects yield multiple drivers, feedbacks, and consequences in the coupled human and natural systems, affecting food security at a great extent. Interconnections among interdependent components require a deeper understanding on earth systems, natural ecosystems, human society, and agricultural systems. Secondly, interdisciplinary works are needed to address food security from crop production to food consumption. Producing more food in the changing environment is the first necessity for food security improvement. With this aim, biotechnology is the primary way to increase crop productivity. However, new approaches to managing farming systems and agricultural landscapes in an environmentally sensitive way could instead be more productive (Benton et al., 2011). Sheeran (2011) even debates that ending hunger does not necessarily require major scientific breakthroughs, sustainable food policy and agriculture development seem to be more critical. The fact is that conclusions from specific-discipline are not always robust; a tight interdisciplinary effort incorporating the latest knowledge updated in various disciplines will be more scientific. Finally yet importantly, cross-scales synthesis is equally as important as interdisciplinary integration. The specific objectives at each scale need to be clarified in the first place: the main objective of field level research is to understand the mechanism through which global change will affect crop growth, crop health, and crop yield. At the regional level, analysing the interactions between crops and their environment throughout the geographical landscapes should be highlighted as priority. Works at this stage include crop model upscaling, crop–climate–soil model integration, and land use mapping and modelling. While at the global level, scenario analysis in global change, vulnerability, policy adaptation, and mitigation should be stressed for the comprehensive food security assessment.

The effective solutions that can relieve food insecurity in short term are welcomed—e.g. food aid (Sheeran, 2011), and stabilizing food price and improving food accessibility (FAO, 2011). However, we have to think more about what role can agriculture play in the long term in again doubling total food production to keep pace with the challenges of population explosion, market fluctuation, diet shifting, climate change, and ecosystem degradation. In this context, scientists are important in finding adaptive strategies for policymakers as well as individual farmers for future food security and sustainability, although they do not have the power to control the global food systems.

In conclusion, we would like to quote Godfray et al. (2010) in Science Special Section for food security: “feeding 9 billion people in the future will require a revolution in the social and natural sciences concerned with food production, as well as a breaking down of barriers between fields. The goal is no longer simply to maximize productivity, but to optimize across a far more complex landscape of production, environmental, and social justice outcomes”.

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