A spatially explicit assessment of current and future hotspots of hunger in Sub-Saharan Africa in the context of global change

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ABSTRACT

Hunger knows no boundaries or borders. While much research has focused on undernutrition on a national scale, this report evaluates it at subnational levels for Sub-Saharan Africa (SSA) to pinpoint hotspots where the greatest challenges exist. Undernutrition is assessed with a spatial resolution of 30 arc-minutes by investigating anthropometric data on weight and length of individuals. The impact of climate change on production of six major crops (cassava, maize, wheat, sorghum, rice and millet) is analyzed with a GIS-based Environmental Policy Integrated Climate (GEPIC) model with the same spatial resolution. Future hotspots of hunger are projected in the context of the anticipated climate, social, economic, and bio-physical changes. The results show that some regions in northern and southwestern Nigeria, Sudan and Angola with a currently high number of people with undernutrition might be able to improve their food security situation mainly through increasing purchasing power. In the near future, regions located in Ethiopia, Uganda, Rwanda and Burundi, southwestern Niger, and Madagascar are likely to remain hotspots of food insecurity, while regions located in Tanzania, Mozambique and the Democratic Republic of Congo might face more serious undernutrition. It is likely that both the groups of regions will suffer from lower capacity of importing food as well as lower per capita calorie availability, while the latter group will probably have sharper reduction in per capita calorie availability. Special attention must be paid to the hotspot areas in order to meet the hunger alleviation goals in SSA.

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1. Introduction

Food security means access at all times by all people to adequate amounts of safe, nutritious, and culturally appropriate food for an active and healthy life (World Bank, 1986). Our current times are regarded as more civilized than any periods before in human history, yet there are still a substantial number of people living in an insecure food situation. According to the Food and Agriculture Organization (FAO), in 2002–2004 approximately 864 million people (14% of the world population) were undernourished (FAO, 2006b). Hunger causes human suffering, enhances the rates of disease and mortality, limits neurological development, reduces labor productivity, and even holds back a nation's economic growth (UN Millennium Project, 2005). Particularly, for young children, the lack of food can be perilous, since

it retards their physical and mental development and threatens their very survival. In 1996, the FAO World Food Summit set a goal of halving the proportion of people who suffer from hunger between 1990 and 2015. This goal was later incorporated into the United Nations' Millennium Development Goals (MDGs), and most countries committed to fight against lack of access to one of the most basic necessities — safe and adequate food resources.

Poverty and low food production are commonly regarded as two important factors leading to hunger (UN Millennium Project, 2005). As a whole, the world produces enough food for its entire population. Countries with a large number of hungry populations, such as India, also produce enough food to feed their entire population (Sanchez and Swaminathan, 2005). Despite the sufficient food supply, many poor people still cannot afford to purchase sufficient food on the market, leading to hunger problems (UN Millennium Project, 2005). Although the Green Revolution has brought higher food production in many parts of the world in the past three decades, the overall food production per capita is experiencing a decline in Africa (FAO, 2006a). Low food production associated with poverty remains the

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determining factor as to why starvation has occurred there (Sanchez and Swaminathan, 2005).

Two indicators are commonly used to monitor the progress of the MDGs to halve the world's hunger, as shown with indicators I and II (UN Millennium Project, 2005). Hunger indicator I gives the percentage of the human population below the minimum level of calorie intake (or dietary energy consumption). This indicator compares the actual calorie intake with the minimum amount of calorie needed for a normal and healthy life. Hunger indicator II provides information on the prevalence of children under five years of age who are underweight. By using these indicators on current levels of undernutrition, light can be shed on the geographical nature of poverty and hunger and how climate change and global economic uncertainties might impact future hunger situations.

Given the number of hungry people in the developing world and the increasingly complex risk to food security, policymakers are faced with an enormous challenge. Freeing people from hunger will require more and better-targeted investments, innovations, and policy actions, driven by a keen understanding of the dynamics, risks and forces that shape the factors affecting people's access to food and the links with nutrition (Von Braun et al., 2005). The national analysis of food security, as most commonly encountered in discussions of hunger and malnutrition in SSA, does not reflect the considerable variation in the food security condition of households within a particular country. Undertaking a spatially explicit assessment allows us to determine how much actual access individuals have to available food, and a closer insight can be gained into what actually might cause their food insecurity, what sort of actions might need to be taken, and where this action should be taken to reduce food insecurity. The importance of subnational studies has been recognized and a first attempt has been made to quantify hunger indicator II by the Task Force on Hunger in the UN Millennium Project (UN Millennium Project, 2005). The task force divides the world into 605 subnational units (provinces, states, districts), and identifies hunger hotspots where the prevalence of underweight children under the age of five is greater than or equal to 20%. Still, for hunger indicator I, insufficient attention has been paid to a spatially explicit assessment. So far, the most detailed measurement of hunger indicator I was provided by FAO. It takes into account food consumption per person and the extent of unequal access to food at a national level.

Climate is and certainly continues to be a factor that has an impact on food security, given the increased frequency of droughts and increasing temperature in the SSA region. Therefore, examining food production in the context of global change (climate change included) is critical in understanding the future situation of food security in SSA. Several studies have been conducted to investigate the possible impact of climate change on crop yields. However, the previous assessments have not identified the climate, socio-economic, and bio-physical changes which could drastically alter the overall food security situation and pose new challenges for future hunger reduction in SSA.

Scientific advances have made several high-resolution datasets available, e.g. current and future projected Gross Domestic Product (GDP) (Grübler et al., 2007) and population data (Grübler et al., 2007). These datasets are valuable to help conduct a spatially explicit assessment of the impact of global change on food security. In this paper, we first assess the current number of people suffering from undernutrition in SSA with a spatial resolution of 30 arc-minutes (about 50 km×50 km nearby the equator). Then, we analyze the impact of global climate change on food production in SSA with the same resolution. Finally, we investigate the future social (i.e., population), economic (i.e., GDP), and bio-physical (i.e., production) changes to identify potential hunger hotspots in order to locate those areas where the greatest challenges exist to fight against hunger in the future. Moreover, we investigate how these future potential hunger hotspots relate to the current undernutrition situation. SSA is selected as a case study, because it is a region with the highest hunger

prevalence in the world, and the absolute numbers of hungry people are increasing (FAO, 2006b).

It should be pointed out that various terms are used to describe nutritional inadequacies, such as undernourishment, malnutrition, undernutrition etc., but there is no universally accepted terminology with an associated definition (see, e.g., FAO (1999) and WHO (1999)). According to FAO, undernourishment refers to the condition of people whose dietary energy consumption is continuously below a minimum dietary energy requirement for maintaining a healthy life and carrying out light physical activity. Undernutrition is used to indicate whether that people's food energy intake is insufficient or that the anthropometric scores of individuals are below selected cut-off points (Nube, 2001). Undernutrition is the result of undernourishment, poor absorption and/or poor biological use of the nutrients consumed. Malnutrition refers to a physical condition or process that results from the interaction of inadequate diet and infection and is most commonly reflected in poor infant growth; reduced cognitive development, anemia, and blindness in those suffering severe micronutrient deficiency; and excess morbidity and mortality in adults and children alike. Undernutrition, overnutrition and micronutrient deficiency are three forms of malnutrition (UNICEF, 1990). In this study, we use a method similar to that in Nube (2001) to assess the nutritional status in SSA and follow the term undernutrition. Since FAO uses the term undernourishment, we remain this original terminology of undernourishment when we present the results from FAO.

2. Method and data

2.1. Undernutrition

Undernutrition is estimated based on the anthropometric data on weight and length of individuals as reported by the Demographic and Health Surveys (DHS) (DHS, 2006). DHS are nationally representative household surveys that provide data for a wide range of monitoring and impact evaluation indicators in the areas of population, health, and nutrition. Standard DHS surveys have large sample sizes (usually between 5000 and 30,000 households) and are typically conducted every five years, to allow comparisons over time. In SSA, surveys are available for 37 of the 48 countries. For children, the surveyed data include: percentage of underweight children and severely underweight children 0–5 or 0–3 years of age. For women, the surveyed data include: weight, percentage with a Body Mass Index (BMI) below 18.5, and percentage with a BMI below 16 for seven age groups (15–19, 20–24, 25–29, 30–34, 35–39, 40–44, >45). In this paper, underweight children and adults with a BMI below 18.5 are defined as population with undernutrition. For children, the same indicator is used by the Task Force on Hunger in the UN Millennium Project, as stated above. For adults, the BMI value of 18.5 is often used as an indicator for nutritional status. For example, WHO (1995) used the cut-off point of 18.5 to classify the nutritional status of a population. If 10–19% of the population has a BMI lower than 18.5, the nutritional situation of the population is poor; 20–29% implies a seriously poor nutritional situation; while if over 40% of the population has a BMI lower than 18.5, immediate intervention must be taken to avoid starvation.

For countries and age groups where DHS data are available, the estimation of undernutrition is straightforward as both the percentage of underweighted children aged 0–5 and the percentage of women with BMI lower than 18.5 are reported. DHS surveys do not report on the prevalence of BMI for men. However, according to Nube and Van Den Boom (2003), there is no major difference of undernutrition between male and female adults in SSA. It can be therefore safely assumed that the nutritional status of women is representative for men in the same age groups. However, for children aged 5–9 we use the nutritional status of children aged five because the anthropometric data on underweight are rarely available for this age group. Similarly, we assume that the prevalence of undernutrition of the age

group 10–14 is the same as that of women aged 15–19. It should be noted that there is still no universally accepted way to measure undernutrition status for the age group 10–14 (WHO, 2006). Whether to apply a BMI value or to use a reference weight to indicate the nutritional status for this age group is a topic of current debate.

The number of people suffering from undernutrition is first estimated at a district level. In this study, 3529 districts are included in SSA. Then, the number of undernourished people in each grid cell is estimated by assuming that the percentage of undernourished people remains the same for all grid cells within a district.

2.2. Impact of climate change on food production

In this study the impact of climate change on crop production is analyzed with the GEPIC model (Liu et al., 2007a,b). The GEPIC model is a bio-physical process-based model that simulates spatial and temporal dynamics of agricultural production and related processes such as weather, hydrology, nutrient cycling, tillage, plant environmental control and agronomics. GEPIC integrates an Environmental Policy Integrated Climate (EPIC, version 0509) model with a Geographical Information System (GIS) by a loose coupling approach. This approach connects the EPIC model with GIS through data exchange, and enables GEPIC to use all the functions of the EPIC model (Liu, in press).

GEPIC calculates daily potential biomass as a function of solar radiation, leaf area index (LAI), and a crop parameter for converting energy to biomass. The potential plant growth is driven by photosythentically active radiation. The amount of solar radiation captured by the crop is a function of LAI and the amount of solar radiation converted into plant biomass is a function of the crop-specific radiation use efficiency. The daily potential biomass is decreased by stresses caused by water shortage, temperature extremes, nutrient insufficiency and soil aeration inadequacy (Williams et al., 1989). The daily potential biomass is decreased in proportion to the severity of the most severe stress of the day. Crop yield is estimated by multiplying above-ground biomass at maturity by a water stress adjusted harvest index. The detailed description about the GEPIC model can be found in Liu et al. (2007b), Liu (in press) and Liu et al. (2008), while the detailed description of the EPIC model can be found in Williams et al. (1989).

The GEPIC model simulates the effects of temperature on crop yield mainly in two ways. First, the daily potential biomass is reduced by temperature stress, as mentioned earlier. Second, GEPIC uses heat unit to determine phenological development and duration of the growing season. The daily heat unit is calculated as the difference between daily mean temperature and a crop-specific base temperature. In addition, temperature is a determinant of soil evaporation and crop transpiration; hence, it affects the availability of soil moisture that sustains crop growth. The GEPIC model simulates the effects of precipitation on crop yield using a concept of water stress. When atmospheric demand for soil moisture exceeds soil moisture supply, a water stress day occurs and potential crop yield is reduced by a certain amount. In the GEPIC model, biomass energy conversion was affected by the level of CO_2 concentration using equations of Stockle et al. (1992), while the biomass conversion factor influences daily potential biomass growth.

Changes in temperature, precipitation and CO_2 concentration are the major variables used in this study to assess the effects of future changes on crop yield. All other factors influencing crop yield are assumed unchanged over time except for crop calendars. In the GEPIC model, an automatic calendar algorithm is developed. The model simulates crop yield considering all specified days as planting dates. The model compares crop yield simulated with all specified planting dates, and selects the highest yield. This algorithm theoretically involves an assumption that local farmers have perfect knowledge in selecting planting and harvest dates. When simulating the impact of climate change, this algorithm allows the farmers to adapt to climate change by adjusting the planting and harvest dates for optimized yield.

Six crops are selected for simulation: cassava, maize, wheat, sorghum, rice and millet. These crops are the most important crops in SSA (Lobell et al., 2008), and combined they account for over half the total calorie intake and over 60% of the calorie intake from vegetal food (FAO, 2006a). Only rainfed agriculture is simulated because it accounts for over 96% of total cereal harvest area and 93% of total cereal production in SSA (Rosegrant et al., 2002). In order to reduce the annual variations of crop yield, 10-year average yield is calculated for two periods: the 1990s (1990–1999) and the 2030s (2030–2039). We select the future period of 2030s mainly due to two reasons. First, this time period is most relevant to large agricultural investments, which typically take 15 to 30 years to realize full returns (Reilly and Schimmelpfennig, 2000). Second, a shorter period will lead to smaller changes in agricultural areas, adaptation, diet patterns, etc. The assessment is conducted with a spatial resolution of 30 arc-minutes because most spatially distributed data are available with this resolution.

The impact of climate change on food production of a certain crop is assessed by comparing the yields in the 2030s with those in the 1990s. Impact ratio (IR) of a crop is defined as the ratio of its yield in the 2030s to its yield in the 1990s. An IR value higher than one means crop yield will increase due to climate change, while an IR value lower than one means the crop yield will decrease. In this assessment, it is assumed that total crop area will not change and the crop types will not change in response to climate change and yield change. However it is expected that crop area is likely to further increase and crop types be adjusted to changes in climate in the future. Nevertheless, we intentionally leave both of these factors unchanged in order to assess the impact of climate change without agricultural area expansion and adaptation measures. The impact of climate change on total food production is assessed with the following equation:

$$IR = \frac{\sum_{c=1}^{6} Y_c^{2030s} \times A_c \times EC_c}{\sum_{c=1}^{6} Y_c^{1990s} \times A_c \times EC_c} \tag{1}$$

where IR is impact ratio, Y is crop yield in kg ha^{-1}, c is crop code, A is crop area in ha, and EC is energy content of a crop in kcal kg^{-1}. Data on EC are obtained from FAO (2006a) and the values of the six crops are reported in Liu and Savenije (2008).

Historical monthly data on maximum temperature, minimum temperature, precipitation and wet days between 1990 and 1999 were obtained with a spatial resolution of 30 arcminute from the Climate Research Unit of the University of East Anglia (CRU TS2.1) (Mitchell and Jones, 2005a). Since daily data are needed, a MOnthly to DAily WEather Converter (MODAWEC) model is used to generate the daily weather data (Liu et al., in press). The future monthly climate data on maximum temperature, minimum temperature, precipitation and wet days between 2030 and 2039 are obtained with the same resolution from the Tyndall Centre for Climate Change Research of the University of East Anglia (TYN SC 2.0) (Mitchell and Jones, 2005b). For the TYN SC 2.0 dataset, runs of the HadCM3 model (Gordon et al., 2000; Pope et al., 2000) for four scenarios are used: A1FI, A2, B1 and B2. The future daily climate data are generated with the MODAWEC model. The CO_2 concentrations in different scenarios are obtained from the ISAM model (reference) from the IPCC climate change report (IPCC, 2001).

Soil parameters of soil depth, percent sand and silt, bulk density, pH, and organic carbon content are obtained from Batjes (2006). Soil parameters are available for 5 soil layers (0–20, 20–40, 40–60, 60–80, 80–100 cm). All other data used for the GEPIC model have been described in detail in Liu et al. (2007b).

2.3. Population and GDP

The recent downscaled population and GDP data by the International Institute for Applied Systems Analysis (IIASA) (Grübler et al., 2007) are used in this paper. The IIASA datasets are produced with a 30 arc-minute resolution for the period 2000–2100. The projections of future population and GDP follow the qualitative scenario characteristics of the original SRES scenarios. We conduct a socio-economic analysis for different scenarios (A2r, B1 and B2), and we found that there is little difference between the different scenarios in terms of GDP and population development in the relatively short time span between the 1990s and the 2030s. In this paper, we only present the socio-economic analysis for the A2r scenario because this scenario tends to highlight potential future problems in Africa the most. The A2r scenario is a revised A2 scenario in order to reflect the recent reorganization that the A2 scenario may likely overestimate the future population (Grübler et al., 2007). The A2r scenario assumes a delayed fertility transition. The A2r scenario also assumes a delayed economic development. In this scenario the reduction in income disparities is initially stagnating, and then remains relatively slow.

The downscaling has been undertaken in two steps. In the first step, the results of population and GDP projections between 2000 and 2100 from the world regional scenarios (Grübler et al., 2007) are disaggregated to 185 countries. In the second step, the national data are further disaggregated to each grid cell with a spatial resolution of 30 arc-minutes by taking into account the income disparities between the rural and urban population. There are several advantages of using the IIASA's GDP and population datasets. First, the datasets are spatially explicit with a spatial resolution of 30 arc-minutes. Second, the data are scenario-dependent, and they are consistent with the original SRES scenarios. Third, structural changes such as urbanization rates are taken into account in different scenarios (Grübler et al., 2007).

2.4. Hotspot analysis of future food insecurity

We combine social, economic and bio-physical factors in order to assess the effects of global change on the future food security.

Population as a social factor can influence total food demand. A higher population growth requires an increasing amount of food supply, and may impose threat to local food security. GDP on a per capita basis as an economic factor can influence the purchasing power. When local food production cannot meet the food demand of the population, a low GDP constrains the people from purchasing food from the market, and therefore results in food insecurity. Crop production as a bio-physical factor can directly influence the local food supply. In SSA, over 80% of cereal and almost all starchy roots were supplied by domestic production in 2000 (FAO, 2006a). Future food supply will have to heavily rely on domestic production when the purchasing power is not strong enough.

Agriculture is the primary source of livelihood for 65% of Africans, and 90% of African agriculture is small-scale (IFPRI, 2004). Hence, changes in crop yield due to climate change may affect most of the African population (IFPRI, 2004) in particular those in the regions where food insecurity exists and people rely on local agricultural production (Brown and Funk, 2008). Climate change may less impact on areas where there is a high degree of urbanization and people buy food on the market. Hence, we focus our analysis on areas where local food production accounts for the major share of the people's food consumption.

We first identified the grid cells with high reliance on food trade and the grid cells with high reliance on local food production. The grid cells with high reliance on food trade are mostly located in the places where urban population is high (e.g., over 1000 people/km^2 in this study). For those grid cells where population density is higher than 1000 people/km^2, it is assumed that all the food is supplied from outside. In low-density rural areas (i.e., <2.5 people/km^2 in this study), it is assumed that people there rely fully on locally produced food. Between these extremes a model has been developed (see SOW/WFP, forthcoming) which allocates the percentage of food imports for each grid cell, also taking into account areas which rely on food aid and areas with a high share of cash crops. We use a threshold of 50% to define those urban areas where subsistence agriculture plays a less important role. These areas are not considered in our analysis since food imports in those areas are substantial.
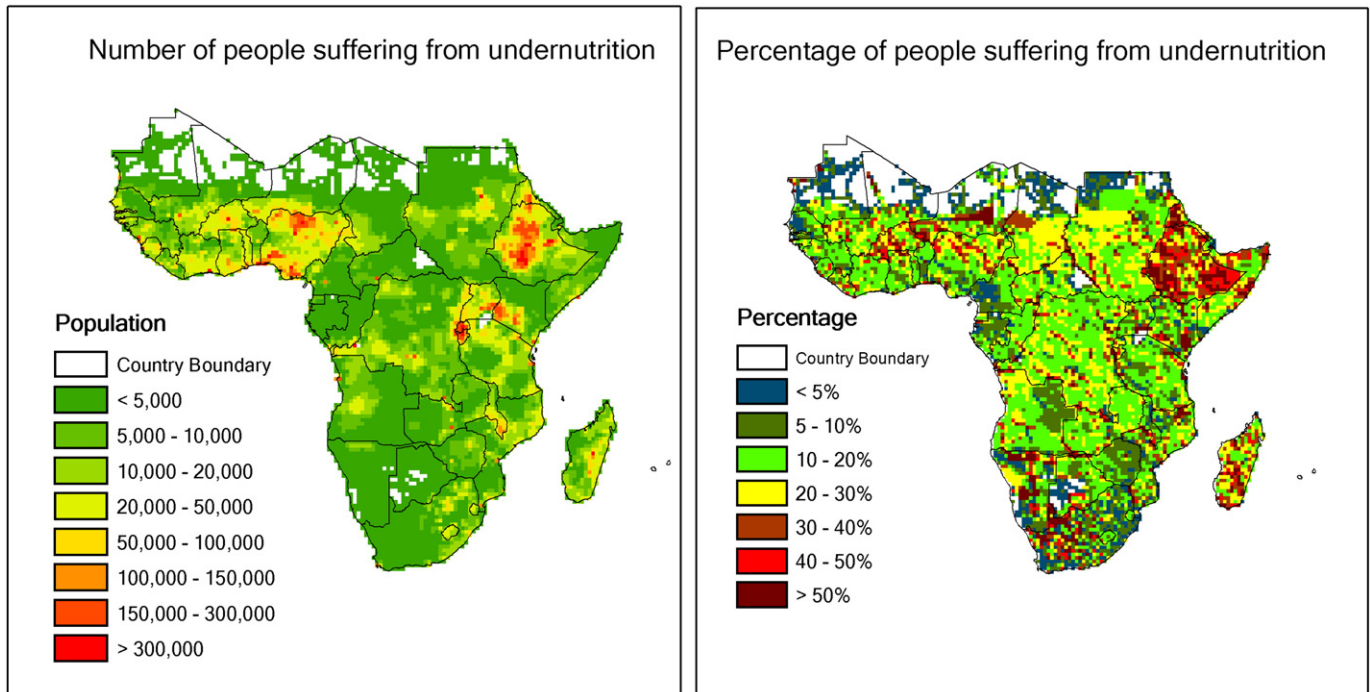

Fig. 1. Number and percentage of people suffering from undernutrition in SSA.
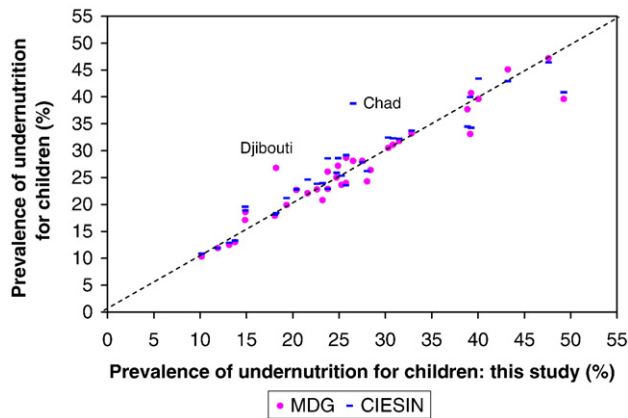
Fig. 2. Prevalence of undernutrition according to the share of young children under five who are underweight: a comparison among this study, MDG and CIESIN.

In order to understand whether the projected changes in yield will impact on the overall calorie availability in the future we calculate relative changes in per capita calorie availability between the 1990s and the 2030s. Moreover, we take into account the spatial distribution of the population density in the 2030s to understand where most people will be affected by this change in the areas of subsistence agriculture.

We undertake a separate analysis for the changes in per capita GDP. In order to determine whether a country or region is able to import more food in the future, we first calculate the overall global increase in per capita GDP between the 1990s and 2030s based on the IIASA scenario database (i.e. 3.6% in A2r scenario) (see Grübler et al. (2007). In case that the growth rate of per capita GDP in a grid cell is higher than the global average per capita growth rate between the 1990s and the 2030s, we assume that in this grid cell people will have more financial capacity to import food in the future than at present. In case that the growth rate of per capita GDP is lower than the global average growth rate we assume that less food per capita will be purchased in that grid cell.

We then combine the changes in per capita calorie availability with the projected future changes in per capita GDP. We select the areas of major concern with decreased per capita calorie availability as well as a slower growth rate of per capita GDP than the global average growth rate between the 1990s and the 2030s. Moreover, we select those areas with a minimum of two people per square kilometer to exclude the areas where little or no population lives.

In the last step, we examine the future hotspots through identifying the areas with current undernutrition problems, lower per capita calorie availability in the future, as well as a lower growth rate of per capita GDP than the global average in the future.

We acknowledge that the above approach to identify hotspots is somehow subjective. However, this study is the first attempt to combine socio-economic and bio-physical factors in order to assess the future hotspot of food insecurity; hence, we prefer to choose a transparent, simple and qualitative method here. A more sophisticated quantitative indicator (e.g. an index based approach) is not used because uncertainty is high in all the projections of the future factors.

3. Results

3.1. Current undernutrition situation in SSA

The spatial distribution of the number and percentage of people suffering from undernutrition is shown in Fig. 1. Grid cells with over 20,000 people suffering from undernutrition are mainly located in many Western African countries, several Eastern African countries (e.g., Ethiopia, Uganda, Rwanda and Burundi), and the eastern coastal area in Madagascar. The highest percentage of people with under-

nutrition is located in Eastern Africa (e.g. Ethiopia), Southern Africa (e.g., Namibia), and some Western countries (e.g. Niger, Burkina Faso). In SSA, approximately 120 million people (all age groups combined) had undernutrition problems in 2000 according to our calculation.

We compared the prevalence of undernutrition estimated in this study with those from other sources. First, both the United Nations' Millennium Development Goal (MDG) project and the Center for International Earth Science Information Network (CIESIN) at Columbia University provide the prevalence of undernourishment according to the share of young children under five who are underweight. MDG provides the data at the national level (http://mdgs.un.org), while CIESIN provides raster data with higher resolutions (e.g., 2.5′ resolution and 0.25° resolution) and shape file data at sub-country levels (http://www.ciesin.org). For comparison, we calculate the prevalence of undernutrition at the country level based on the high-resolution data from our study (i.e. 0.5° resolution) and CIESIN (i.e., 2.5′ resolution). Our results compare very well with those from both MDG and CIESIN in most countries (Fig. 2). Only some countries (e.g., Djibouti and Chad) have large differences. But for both Djibouti and Chad, our results are close to those from at least one source of MDG and CIESIN.

Second, both the MDG database and FAO (2006b) provide the prevalence of undernourished people, and both sources share the same results. When comparing the results from these two sources with ours, we find that the total number of people suffering undernutrition estimated in this study is 39% lower than the total number of malnourished people from MDG and FAO. Particularly, our results show lower prevalence of undernutrition in Central, Eastern, and Southern Africa (Fig. 3). In agreement with our findings, several other studies have also argued that FAO overestimates the prevalence of undernutrition in SSA (Svedberg, 1999; Nube, 2001). For example, Nube (2001) estimates the prevalence of undernutrition in 13 countries in SSA, and calculates a prevalence of 5–18% in contrast to 14–48% according to FAO for adult women in SSA.

The different approaches to estimate the prevalence of under-nutrition or undernourishment is the main reason for the above discrepancy. FAO estimates undernourishment based on its Food Balance Sheets. The sheets report food trade, production, and use by commodity at a national level. Food consumption is calculated as a residual item (consumption=production+imports−exports−feed use −seed use−industrial waste). The national average consumption is distributed over population to estimate per household availability of calories through income distribution information. With a cut-off point for per capita consumption, nutritional status is quantified at the household level. Total number of undernourished population in a country is estimated by aggregating the undernourished people in all households. For many years the FAO method of estimating under-nourishment has been criticized as being unnecessarily complicated and sensitive to assumptions (Svedberg, 1999; Nube, 2001). Svedberg (1999) reveals that the FAO method is highly sensitive to relatively
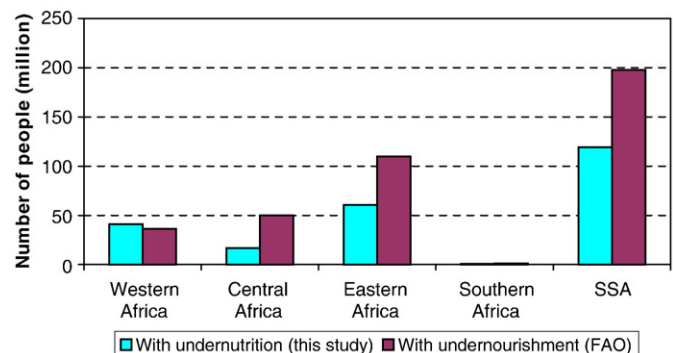

Fig. 3. Comparison of the number of people with undernutrition from this study and the number of malnourished people from FAO (2006b).

small "errors" in the exogenous parameters. For the FAO method, by adjusting the calorie availability by plus/minus 10%, distribution parameter by plus/minus 0.05 and calorie cut-off point by plus/minus 10%, the prevalence of undernourishment in SSA can be ranged from 21% to 61% in 1990–92 (Svedberg, 1999). The ranges of the three parameters are all very possible considering the large uncertainty of their estimation from FAO. The prevalence of undernourishment is wide enough to challenge the accuracy of the estimation by FAO. In contrast, anthropometric measurements are more reliable and relevant for all purposes for which indicators of undernutrition are needed (Svedberg, 1999). There are several advantages of the anthropometrics method, e.g. representativeness of the anthropometric data for individuals, simplicity, accuracy and low estimation costs, etc. Although confronting many critics, FAO still remains the most widely used source of information for the number of hungry people. The reasons are multi-folded, and include the fact that FAO was the first organization conducting the relevant study, and that FAO is a leading and influential organization for global food studies. Nevertheless, comprehensive estimation of the prevalence of undernutrition must be done to direct reasonable food policies in light of the large discrepancy of results from different sources. Therefore, efforts are urgently required in order to bring together the world experts to discuss the best approach to estimate the prevalence of undernutrition and to find consensus, as well as best practice guidelines.

3.2. Impact of climate change on crop production

In this paper, we assess the impact of climate change on crop production by considering the simultaneous change in CO_2 concentration. Climate change and change in CO_2 concentration are two closely related processes. Climate change is, to a large extent, a result of the increasing amount of CO_2 emissions to the atmosphere. Hence, they should be considered together when conducting an impact assessment.

Figs. 4–7 present the impact ratio of climate change (including the CO_2 change, we use "climate change" in this paper) on crop yield for six crops in four scenarios. The results show that all climate scenarios lead to very similar patterns of yield change. This is because, in the 2030s, there is little difference among the four climate scenarios. According to our results, the yield of wheat will be dominantly reduced across SSA in the 2030s compared to the 1990s, which is indicated by the impact ratio being generally lower than one in all scenarios (Figs. 4–7). The optimal temperature of wheat is generally between 15–20 °C, depending on the varieties of wheat (e.g., winter or spring wheat). The annual average temperature across SSA is already above this optimal temperature in the 1990s during the crop growing period. Due to global warming, temperatures will further increase until the 2030s, leading to reduction of crop yield of wheat. In contrast, millet will benefit from climate change in almost the entire
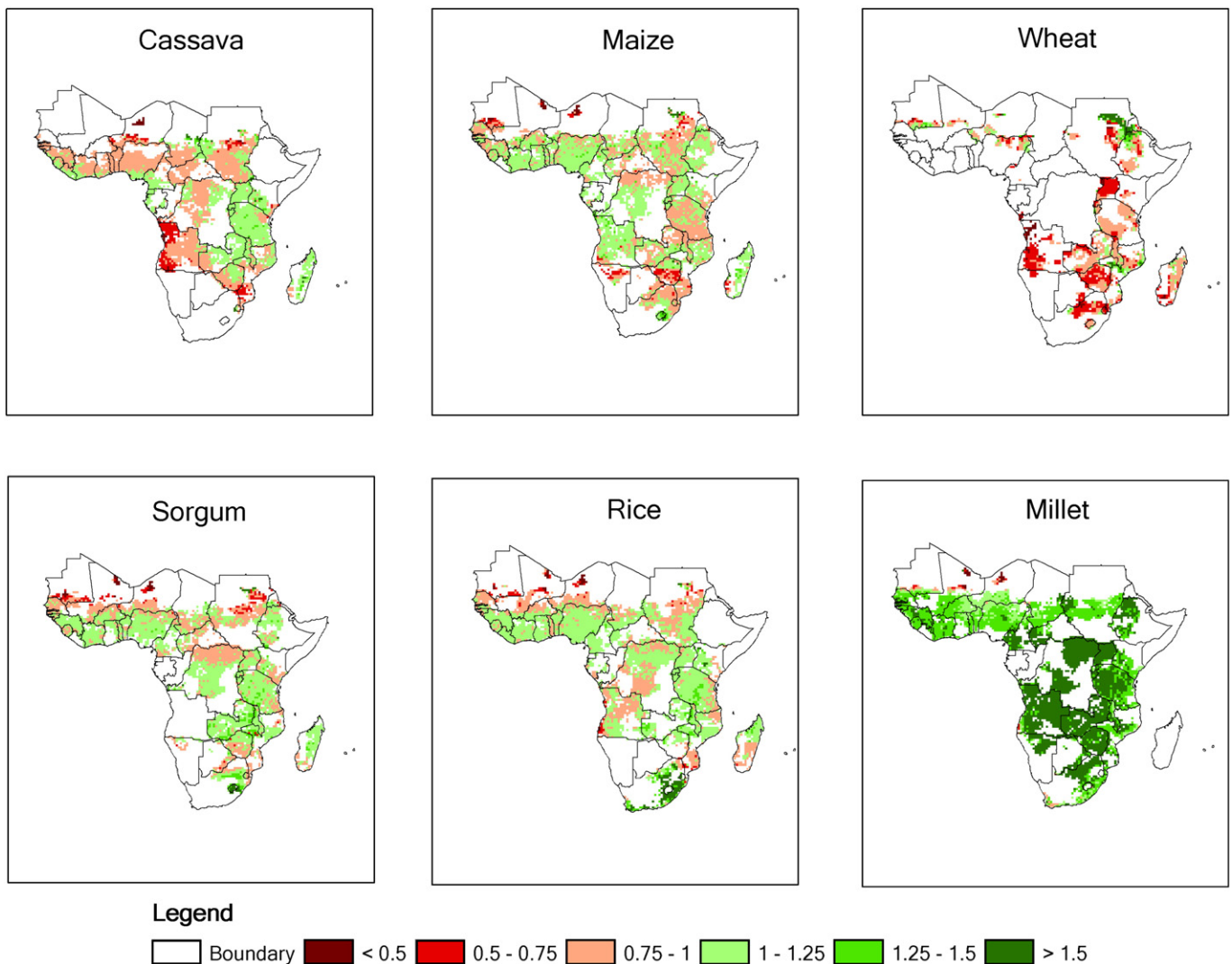

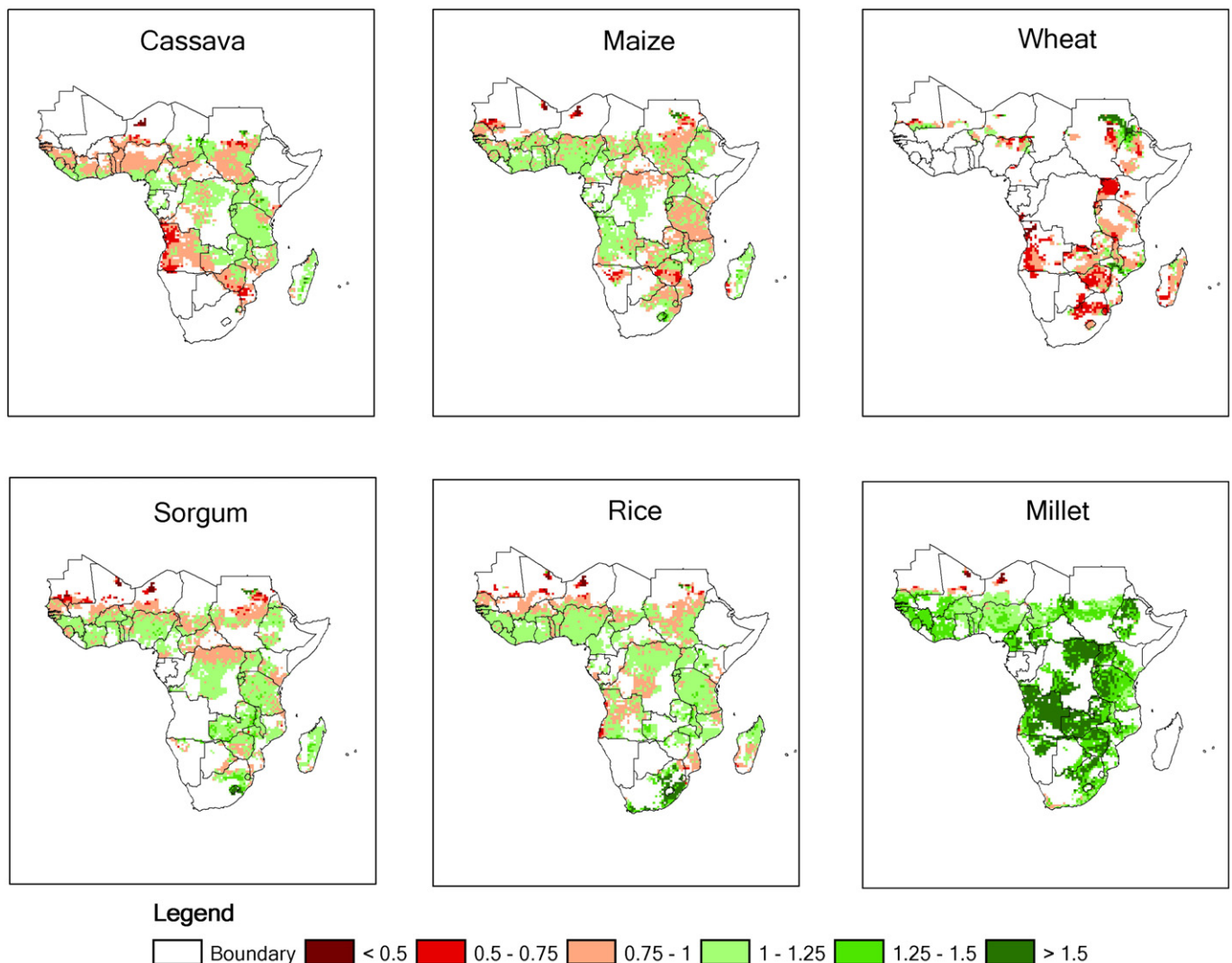Fig. 4. Impact ratio of climate change on crop yield in Africa (A1FI scenario).

Fig. 5. Impact ratio of climate change on crop yield in Africa (A2 scenario).

SSA. Millet has an optimal temperature of around 30 °C. Climate change will result in temperature close to this optimum across SSA; as a result, crop yield of millet increases. Both cassava and sorghum have an optimal temperature of 27.5 °C. The impact ratios of both crops show similar spatial patterns, e.g. lower than one in most of the semiarid area along the Sahel desert and southern part of Zimbabwe and higher than one in large parts of Eastern Africa. Both maize and rice have an optimal temperature of 25 °C. The yield of both crops will be reduced along the Sahel desert. In other regions, rice may benefit more from global climate change than maize. As a C3 crop, rice can benefit more in terms of crop yield from the increased CO_2 concentration than maize (a C4 crop). This can partly explain the different responses of rice and maize to future climate change.

According to our estimate, for SSA as a whole, climate change will lead to 16–18% lower yield for wheat, 7–27% higher yield for millet, 5–7% higher yield for rice, and 3–4% higher yield for maize, depending on different scenarios (Fig. 8). For sorghum and cassava, changes in crop yield are very small. For six crops as a whole, climate change will lead to a slight increase of crop yield by 1.6–3.3% (Fig. 8). The changes in crop yield are well explained by the change in temperature, although other climatic factors also play roles. For example, the annual average temperature in the 1990s was 20.34 °C in wheat harvest area in SSA. This temperature is slightly higher than the optimal temperatures of most wheat varieties. In the future, climate change will lead to higher

temperatures, which are even further away from the optimal temperatures of wheat. Partly due to this, crop yield of wheat will decrease. Another example, in the harvest area of millet, the annual average temperature was 27.27 °C in the 1990s, lower than the optimal temperature of millet. Climate change will lead to temperatures ranging from 28.30 °C to 28.54 °C in the 2030s depending on different scenarios. These temperatures are closer to the optimal temperature of millet; as a result, there will be a general increase in the crop yield of millet in SSA.

To assess the impact of climate change on the production of all studied crops as a whole, we sum up the available calories from local crop production in the 1990s and 2030s, and calculate the impact ratio values (see Eq. (1)), or the ratio of total calories in the 2030s to that in the 1990s. The results are shown in Fig. 9 for A1FI, A2, B1 and B2 scenarios. The national average impact ratios are indicated in Fig. 10 for the four scenarios. In seven countries, climate change will result in a reduction in crop yield in all scenarios. These include Mauritania, Congo, Gabon, Botswana, Swaziland, Zimbabwe, and Angola. Adaptation and mitigation measures should be taken soon to combat the adverse effect of climate change on crop production. In contrast, in 23 countries, climate change will lead to higher crop yield in all scenarios. These countries include Lesotho, Madagascar, Eritrea, Togo, Ivory Coast, Equatorial Guinea, Nigeria, Burundi, Burkina Faso, Benin, Uganda, Ghana, South Africa, Liberia, Ethiopia, Guinea-Bissau,
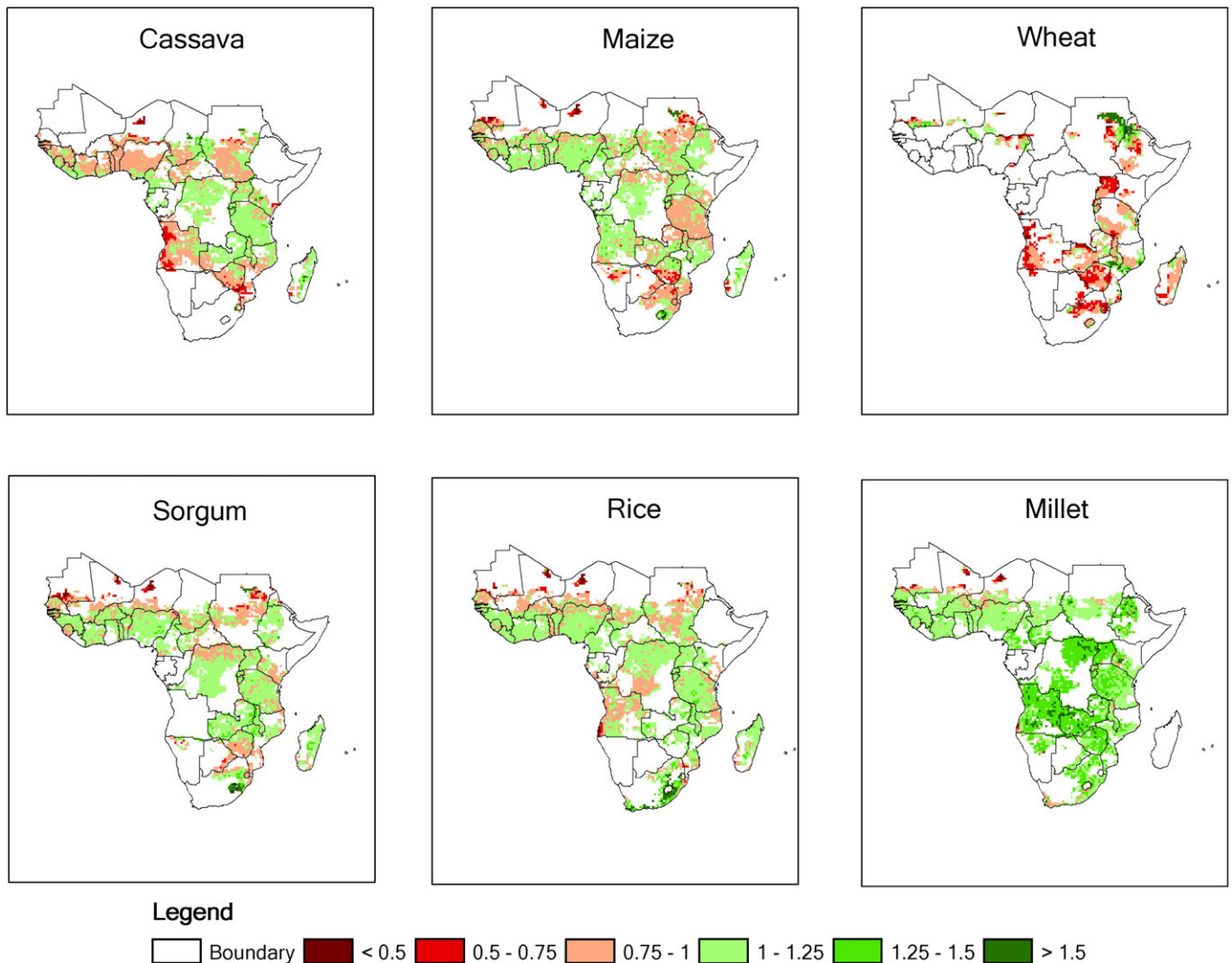
Fig. 6. Impact ratio of climate change on crop yield in Africa (B1 scenario).

Rwanda, Guinea, Sierra Leone, Kenya, Malawi, Senegal, and Gambia. In other countries, crop yield may increase or decrease depending on different scenarios.

Our study reveals a slightly positive change in crop yield for six crops as a whole in SSA. While wheat has a sharp decrease in crop yield, for all other crops, the yield will be much higher (e.g., for millet), slightly higher (e.g., for maize and rice), or remain almost unchanged (e.g., for cassava and sorghum). The general conclusion from this study – or a slightly higher yield in SSA in the 2030s compared to the 1990s – agrees well with some studies (e.g. Adejuwon (2006)) which predict an increase in crop yield in the first half of the 21st century, while it contradicts several others that indicate a decrease in crop production in Africa (Parry et al., 1999, 2004; Reilly and Schimmelpfennig, 1999; Jones and Thornton, 2003). Here, two issues need to be pointed out. First, this study assesses the impact of climate change for each grid cell. The assessment considers the different climatic conditions in all the grid cells. Many previous studies mainly focus on some specific sites, and interpolate the results to a large area (e.g. Rosenzweig and Parry (1994), Adejuwon (2006)); or they assess the impact for different countries or regions as a whole without considering the local variations (e.g. Parry et al. (2004)). Second, a number of previous studies often ignore the change in CO$_2$ concentration; hence, the "fertilization" of CO$_2$ is not taken into account, likely leading to an underestimation of crop yield in the future.

Direct comparison of the impact of climate change on crop production between this study and other studies is difficult because they encompass a range of different periods, regions and crops, and the uncertainty ranges can come from several sources such as spatial variability in yield, uncertainty in climate information, and different crop simulation methods (Challinor et al., 2007). We compare our results with the most recent studies. Lobell et al. (2008) project the potential yield change in 2030 with statistical crop models and climate projections from 20 general circulation models. There are several similar findings reported in Lobell et al. (2008) and the current study. First, both studies suggest that maize and wheat in Southern Africa will have lower yields in the 2030s. Second, the yield of cassava will generally not be highly affected by climate change. Third, rice will have a higher yield in Eastern and Southern Africa, and lower yield in Central Africa. Despite these similar findings, discrepancy exists between the two studies. For example, Lobell et al. (2008) found a high probability of lower maize yield in SSA in the future, while this study indicates slightly higher maize yield. The reason for the difference may be partly due to the fact that Lobell et al. (2008) ignored the effect of the change of CO$_2$ concentration, which leads to a somehow underestimation of crop yield in the future. When not considering the change of CO$_2$ concentration, the GEPIC model also shows a lower yield of maize, e.g. in the A1FI scenario (data are not shown here). Parry et al. (2004) estimate the current and future yield at a national level using yield transfer functions. They conclude that
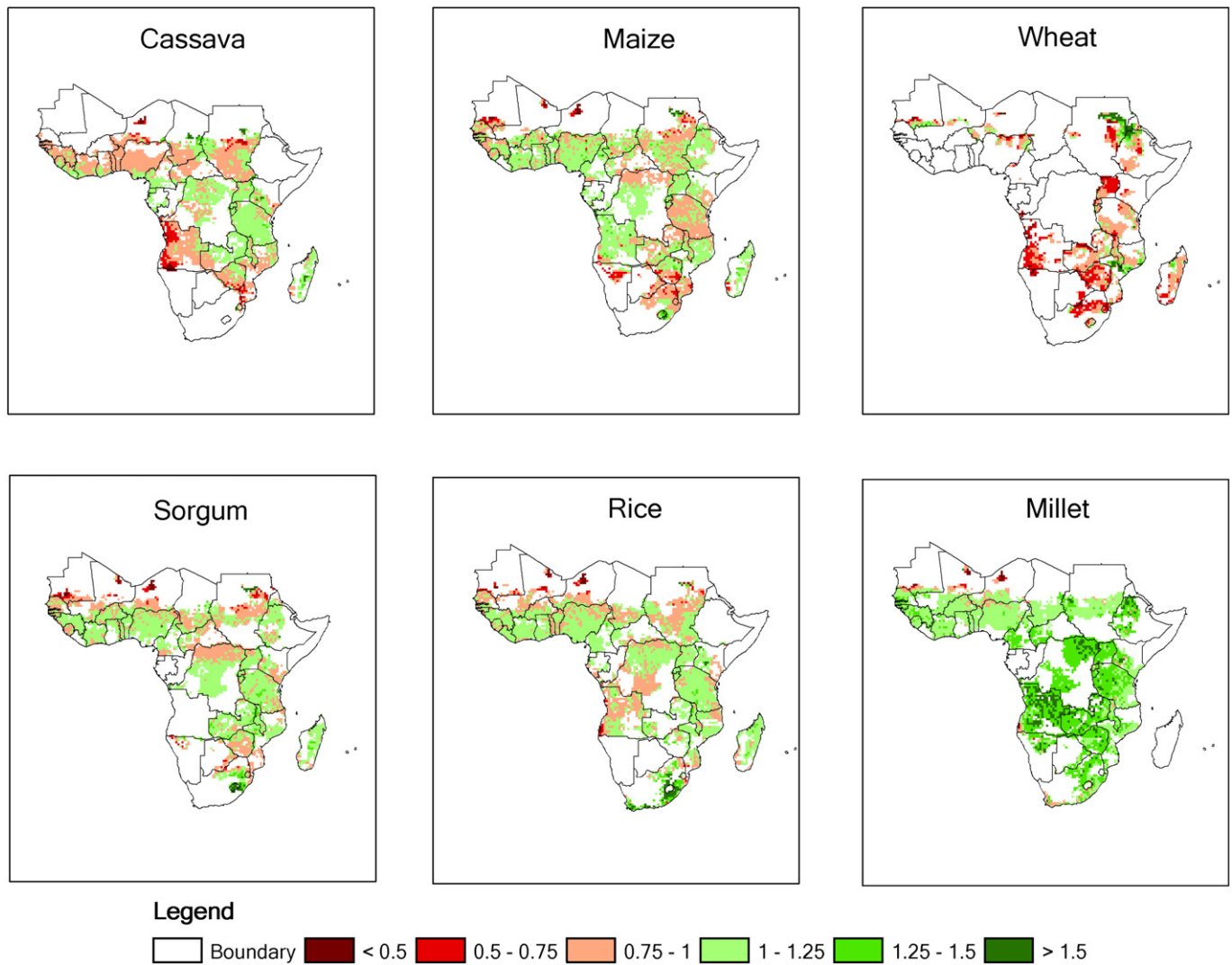
Fig. 7. Impact ratio of climate change on crop yield in Africa (B2 scenario).

total crop yield in Africa may decrease up to 30% in the 2080s compared to 1990. Parry et al. (2004) assess crop yield change for wheat, maize, rice, and soybean, but they do not estimate the change for cassava, sorghum and millet. However, the latter three crops are very important for calorie intake in Africa. Particularly for millet, crop yield may greatly increase in the future according to our calculation. Besides the different studied periods, the selection of different crops is a major reason for the difference in the yield change between this study and Parry et al. (2004).

Fig. 8. Impact ratio of climate change for six crops in SSA (with physiological CO_2 effect).

Jones and Thornton (2003) use a CERES-Maize model and climate output of a global circulation model, and estimate an overall reduction of 15% in maize production in SSA by 2055. This conclusion contradicts our findings. Besides the difference in the studied periods, two major reasons explain the contradiction. First, Jones and Thornton (2003) do not take into account the "fertilization" effect of CO_2 in the atmosphere. Second, the different models used (i.e. GEPIC in this study versus CERES-Maize in Jones and Thornton's) may be another important reason for the difference, although a comparison of the models is beyond the scope of this paper.

3.3. Change in per capita calorie availability between the 1990s and the 2030s

As we have demonstrated in the last section climate change is likely to affect Africa differently at different locations. Even though the overall yields will not decrease according to this study, per capita calorie availability may decrease when considering population growth. We calculate the change in per capita calorie availability between the 1990s and the 2030s (see Fig. 11). Grid cells with an increase in per capita calorie availability are displayed in blue tones. A substantial increase in per capita calorie availability can only be found in many parts in South Africa, Zimbabwe, Botswana and Mozambique. Noticeable increase can also be found in a confined
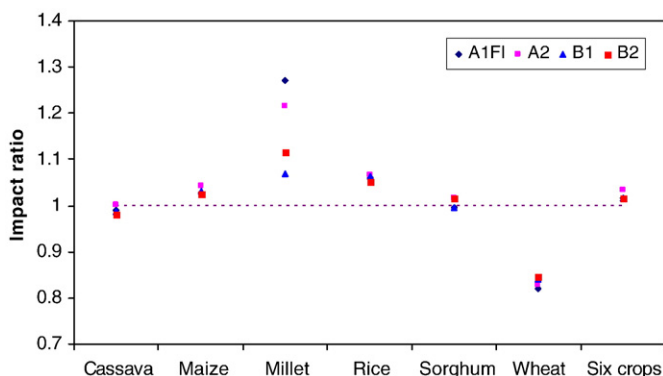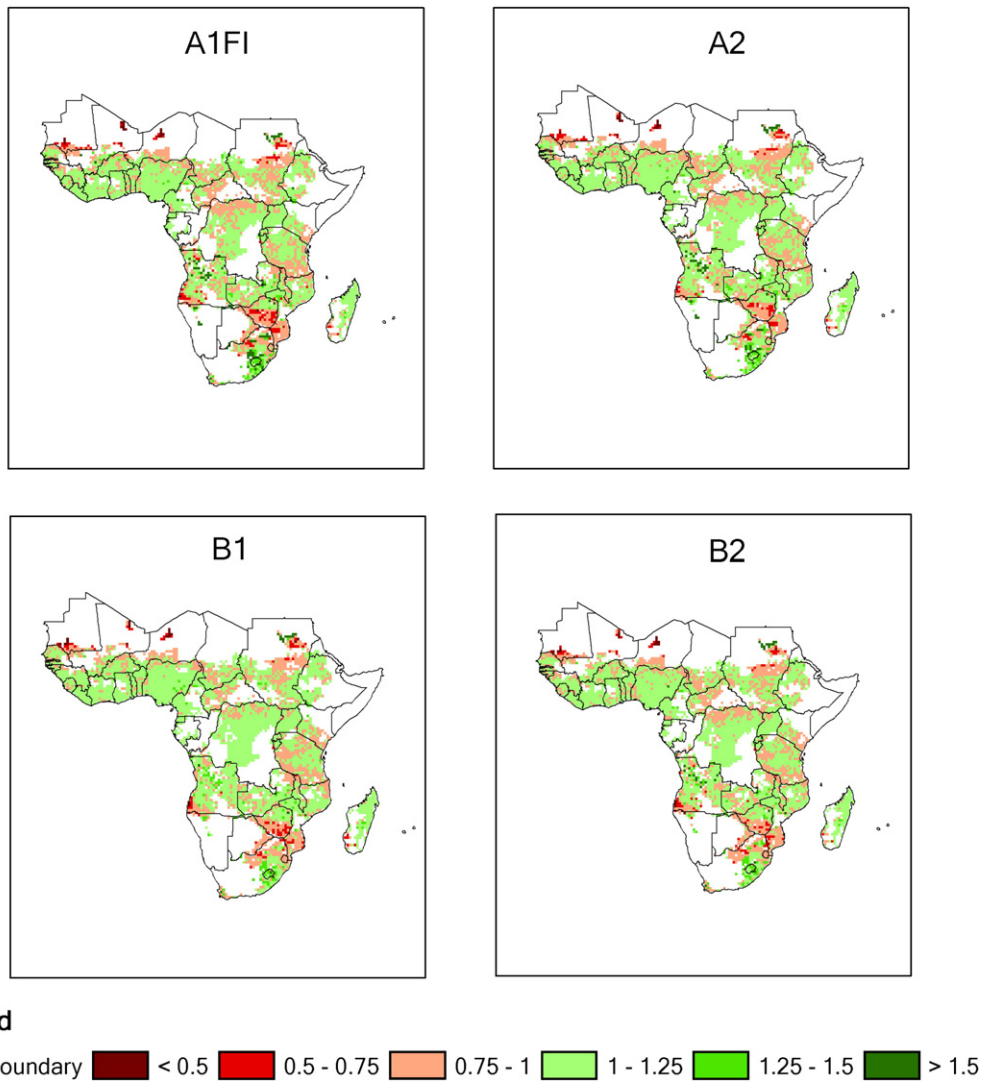
Fig. 9. Impact ratio of climate change on crop production in Sub-Saharan Africa for A1FI, A2, B1 and B2 scenarios.

border region of Chad, Niger and Nigeria. Grid cells with decreased per capita calorie availability between the 1990s and the 2030s are shown in red, orange, yellow and green tones. In order to visualise the distribution of the population in the same map, we show the higher population density with an increasing strength of red, orange, yellow, green and blue tones. Areas with a high degree of urbanization are displayed in a separate layer with the colour black, while the areas currently relying mainly on subsistence agriculture are shown with other colours on the maps. Areas with strong red and brown tones are of major concern. These areas are likely to face very serious undernutrition problems. Population there relies to a high degree on subsistence agriculture. These areas are located in Guinea, Ivory Coast, Sierra Leone, Liberia, Niger, Nigeria, Chad, Northern Sudan, Ethiopia, Angola, Kenya, Uganda, Democratic Republic of Congo, Uganda, Madagascar, and northern Tanzania.

3.4. Change in per capita GDP between the 1990s and the 2030s with respect to population

It can be argued that the hotspots located in Fig. 11 may change when there will be a substantial increase in purchasing power in the 2030s. We therefore undertake a separate analysis looking at potential future changes in the capacity to import food. By calculating the growth rate of GDP per grid cell with respect to the

global average growth rate between the 1990s and 2030s (see the method described in Section 2.4), we find that many areas in Africa are not likely to import more food on a per capita basis in the future. In order to indicate the locations where most of the people will be living we add population density numbers for 2030s to Fig. 12. Particularly the areas located in southern Mali, Burkina Faso, Mozambique, Tanzania, Uganda, Somalia, and Madagascar are likely to experience a dramatic decrease in the capacity to import food on a per capita basis than currently (see Fig. 12). These regions have the lowest growth rate of GDP in SSA. Other areas located in south-western Ivory Coast, Ethiopia, southern Uganda, and Angola might also experience a lower capacity of being able to import food (see Fig. 12) as the growth rates of GDP in these areas are 30–60% lower than the world average growth rate between the 1990s and the 2030s. Areas with a high population density in the 2030s and the highest growth rate of GDP between the 1990s and the 2030s are located in Sudan, southern Kenya and Central Zambia (see Fig. 12). Other population-dense areas such as western Guinea, a large part of Ghana, Togo, Benin, Nigeria, western part of Central Africa, Zambia, Zimbabwe, northern part of Kenya, and some places in the Democratic Republic of Congo also have a projected increase in the capacity of being able to import food in the future. The effect of the increasing purchasing power may compensate the decrease in per capita calorie availability in these areas.
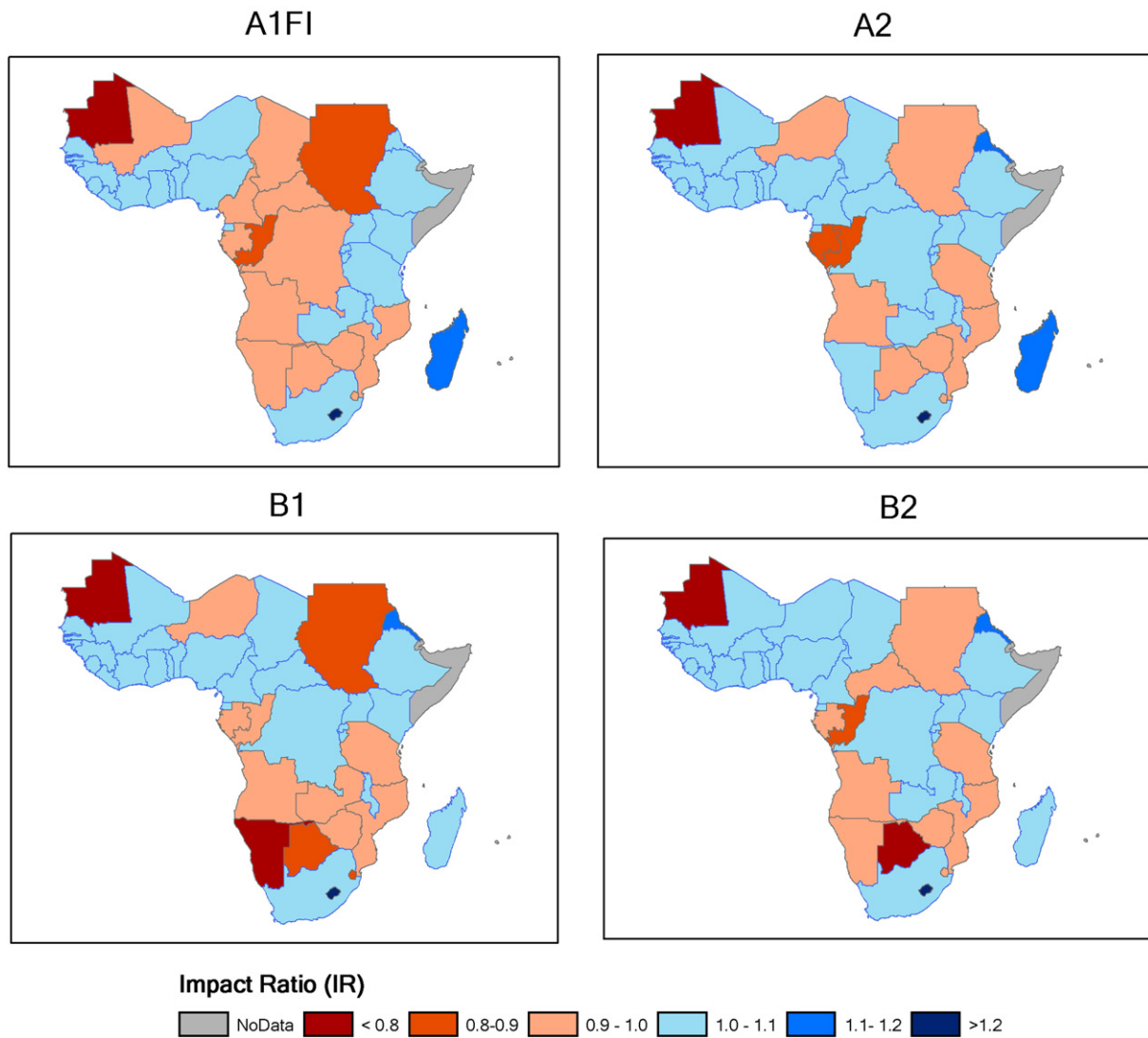
A1FI

A2

B1

B2

Impact Ratio (IR)

| NoData | < 0.8 | 0.8-0.9 | 0.9 - 1.0 | 1.0 - 1.1 | 1.1- 1.2 | >1.2 |

Fig. 10. National average impact ratio of climate change on crop production in Sub-Saharan Africa for A1FI, A2, B1 and B2 scenarios.

3.5. Comparison of current hotspots of undernutrition with future potential hotspots of food insecurity in the 2030s

As outlined in Section 2.4 we identify the future hotspots of food insecurity by identifying those grid cells where per capita availability of calorie will decrease and the growth rate of per capita GDP will be below the world average between the 1990s and the 2030s. Two hotspot classes are categorized. In both classes, the capacity of being able to import food will decrease between the 1990s and the 2030s. In the first class (hotspot), per capita calorie availability decreases by 0–30%, while in the second class (severe hotspot), per capita calorie availability decreases by over 30%. Grid cells of the hotspot is shown single shaded in Fig. 13, while grid cells of the severe hotspot are shown in Fig. 13 cross-shaded. We also examine how these potential hotspots are related to the current undernutrition hotspots. Such a comparison allows us to identify areas where more effort is needed in terms of future actions (such as food aid and development programs).

The results show that, for densely populated regions (population density>20,000 people/km²), regions in northern and southwestern Nigeria, Sudan and Angola with a currently high number of people with undernutrition might be able to improve their food security situation due to either an increase in per capita calorie availability or an increase in the capacity to import food. Other regions located in Ethiopia, Uganda, Rwanda, Burundi, southwestern Niger, and Mada-

gascar with current undernutrition problems will likely remain hotspots of food insecurity in the future. In these regions, the capacity to import food will be lower in the future, while per capita calorie availability will be reduced by 0–30%. Regions located in Tanzania, Mozambique and the Democratic Republic of Congo might face more serious undernutrition in the future. These regions will have a lower capacity to import food in the future, while per capita calorie availability will be reduced by over 30%.

4. Conclusion

This paper deals with a spatially explicit assessment of current and future hotspots of food insecurity in Sub-Saharan Africa (SSA). The number of people suffering from undernutrition is assessed with a spatial resolution of 30 arc-minutes. The impact of climate change on crop production is analyzed for six major crops in SSA with the same spatial resolution. The hotspots of future food insecurity are identified in the context of future global changes in population, GDP, and crop production.

The results show different patterns of yield change for six major crops in SSA. Wheat will have a sharp reduction in crop yield, while the yield of millet will increase due to climate change. The yield of other crops will be less affected by climate change than these two crops. However, when taking population growth into account, most
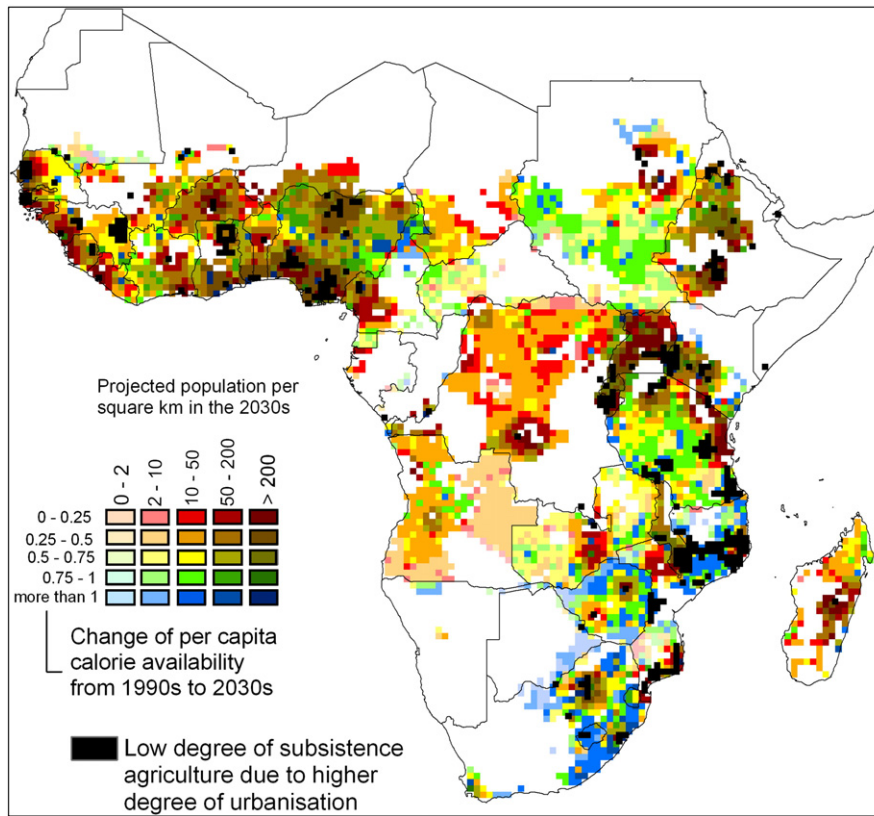
Fig. 11. Changes of per capita calorie availability from the 1990s to the 2030s in relation to population density of the 2030s and low degree of subsistence agriculture. For change of per capita calorie availability, the legend 0–0.25 means reduction of 100–75%, 0.25–0.5 means a reduction of 75–50%, 0.75–1 means a reduction between 25 and 0%, and more than one means that per capita calorie availability will increase between the 1990s and the 2030s. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
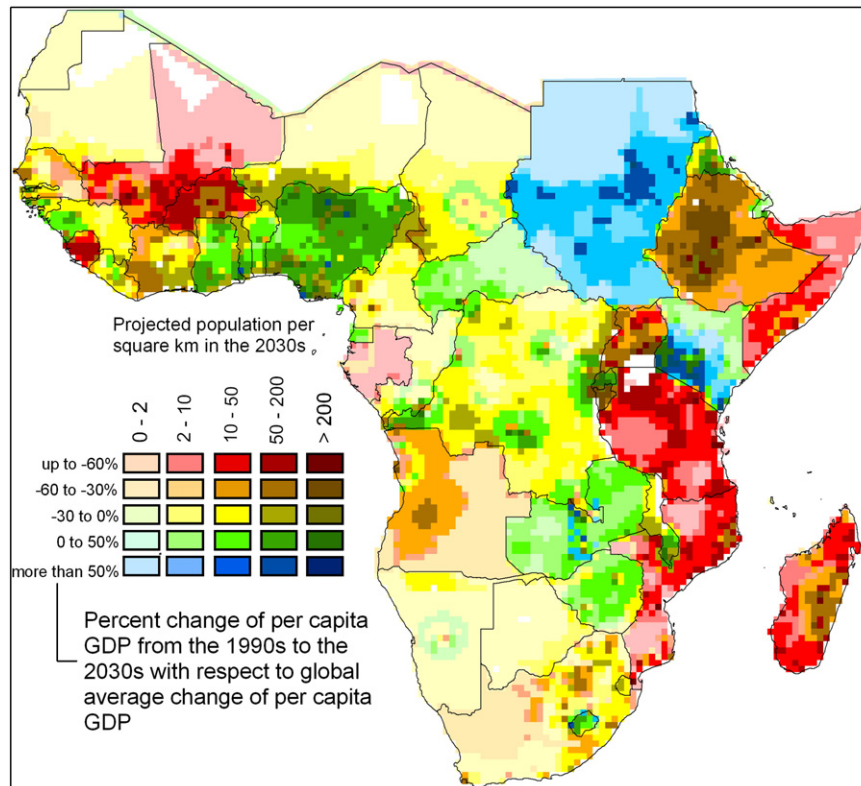

Fig. 12. Changes in per capita GDP from the 1990s to the 2030s in relation to projected population density in the 2030s. A positive percentage in the legend indicates a higher growth rate of GDP than the world average growth rate between the 1990s and the 2030s. For instance, the value of 50% means the growth rate of GDP is 50% higher than the world average growth rate (i.e. 3.6%), or it means the growth rate of GDP is 5.4%. A negative percentage in the legend indicates a lower growth rate of GDP than the world average growth rate between the 1990s and the 2030s. For instance, the value of −30% means the growth rate of GDP is 30% lower than the world average growth rate, or it means the growth rate of GDP is 2.52%.
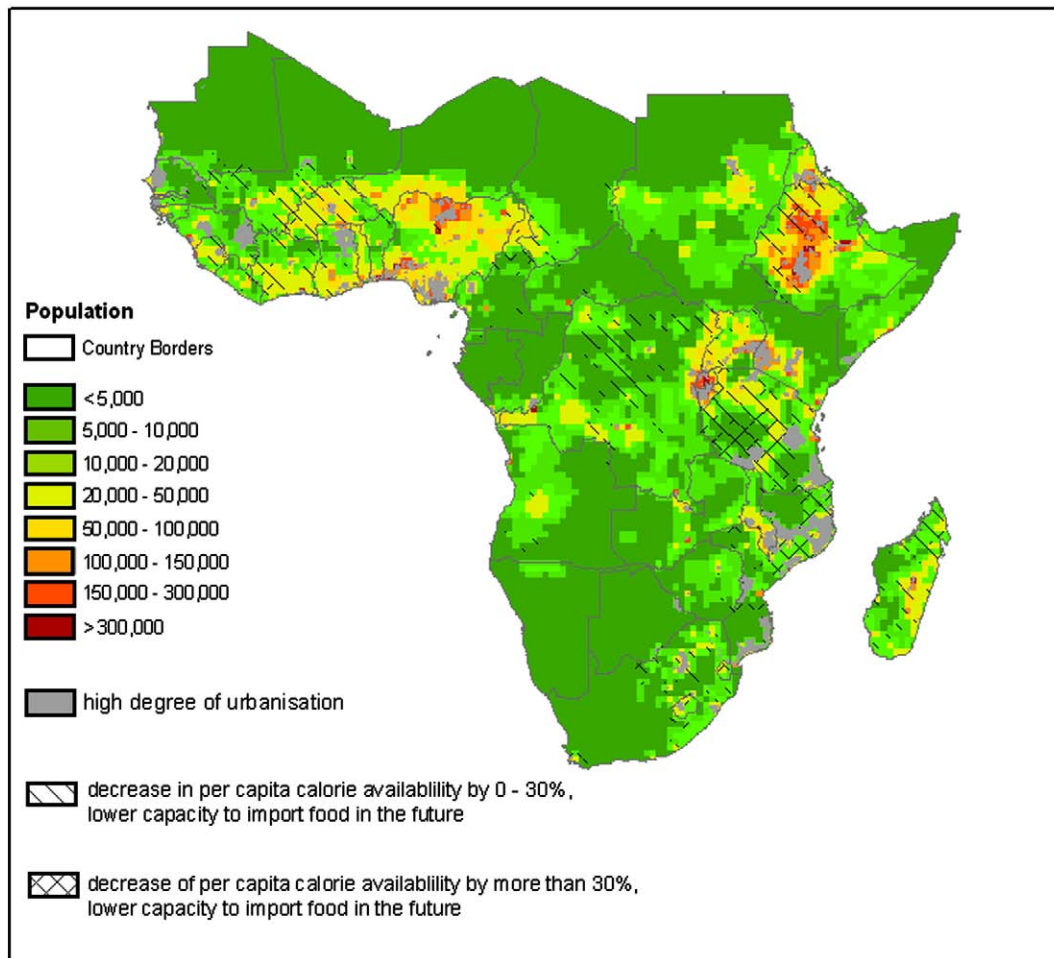
Fig. 13. Number of people with current undernutrition problems in relation to future potential hotspots of food insecurity in the 2030s.

African countries will experience lower per capita calorie availability in the future. By considering spatially explicit information on per capita GDP, we conclude that certain regions such as central–northern Ethiopia, southern Uganda, southwestern Niger, northern Tanzania, and countries such as Rwanda and Burundi will most likely continue to be trapped in poverty.

On the other hand, other regions located in southwestern Niger, Nigeria and Sudan are predicted to be able to import more food and might therefore manage to reduce food insecurity. However, special attention has to be paid to countries such as Tanzania, Mozambique and the Democratic Republic of Congo because these countries are predicted to face more serious undernutrition in the future as both the capacity to import food and the per capita calorie availability are predicted to be lower in the future.

In this scenario study we intentionally consider limited adaptive capacity trying to reflect some of the constraints of subsistence agriculture under extreme poverty. The study intentionally does not consider new crop distributions such as the replacement of sorghum by maize and vice versa, or the use of new crop varieties which are more adapted to harsher climate conditions. Alternative crop management options such as irrigation are also not considered. However, we account for adaptations in the crop calendar. The research is therefore seen to show the current baseline under business as usual and considering future climate chance only — hence people will stick to the location and current distribution of current crop types and crop varieties. This in some way is a limitation of the study as people might change to other crops. Therefore we intend to consider alternative

scenarios of higher adaptive capacities in a follow up study. We would then simulate what crops grow best in certain areas and in which regions crop acreage can be extended.

This paper is constrained by several limitations. First, although four climate scenarios are used, only results from one climate model, or the HadCM3 model, are used for the simulation of climate change on crop production. Projections of climate change have high uncertainty, and results simulated with climate data from other models may provide a different picture of the effect of climate change. Future research needs to combine climate scenarios from more climate models for a more comprehensive study. Second, there may also be uncertainties in the spatially explicit data on future GDP and population. Third, the criteria of identifying the hotspots of food insecurity contain certain subjective elements as certain thresholds have to be chosen when comparing current with future hotspots. Despite these limitations, we have made the first attempt to address the spatially explicit assessment of the current and future hotspots of food insecurity in SSA. The results can provide valuable information for decision makers to set priority areas to combat hunger in SSA.

The study indicates that dramatic adaptive measures need to be taken in the next 30 years to improve the situation of food security in SSA. The spatially explicit assessment allows targeting the areas where urgent actions are needed to prevent future hunger. These actions range from improving crop varieties, optimizing crop types, extending crop area, and increasing crop yield through better water and fertilizer management. In case that the adaptive measures are not taken, several countries such as Tanzania, Mozambique and the Democratic Republic

of Congo will continue to remain highly food insecure. International food aid is a necessity to help enhance the food security in these countries when adaptive measures fail.

Acknowledgements

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