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Global hot-spots of heat stress on agricultural crops due to climate change

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ABSTRACT

The productivity of important agricultural crops is drastically reduced when they experience short episodes of high temperatures during the reproductive period. Crop heat stress was acknowledged in the IPCC 4th Assessment Report as an important threat to global food supply. We produce a first spatial assessment of heat stress risk at a global level for four key crops, wheat, maize, rice and soybean, using the FAO/IIASA Global Agro-Ecological Zones Model (GAEZ). A high risk of yield damage was found for continental lands at high latitudes, particularly in the Northern Hemisphere between 40 and 60°N. Central and Eastern Asia, Central North America and the Northern part of the Indian subcontinent have large suitable cropping areas under heat stress risk. Globally, this ranged from less than 5 Mha of suitable lands for maize for the baseline climate (1971–2000) to more than 120 Mha for wetland rice for a future climate change condition (2071–2100) assuming the A1B emission scenario. For most crops and regions, the intensity, frequency and relative damage due to heat stress increased from the baseline to the A1B scenario. However for wheat and rice crops, GAEZ selection of different crop types and sowing dates in response to A1B seasonal climate caused a reduction in heat stress impacts in some regions, which suggests that adaptive measures considering these management options may partially mitigate heat stress at local level. Our results indicate that temperate and sub-tropical agricultural areas might bear substantial crop yield losses due to extreme temperature episodes and they highlight the need to develop adaptation strategies and agricultural policies able to mitigate heat stress impacts on global food supply.

1. Introduction

The environment within which agricultural crops and agronomic practices developed over the past 10,000 years is rapidly changing due to human-induced climate change (IPCC, 2007b). The rate of global warming is expected to continue increasing if no mitigation efforts take place to reduce the carbon intensity of the world economy and the consequent emission of green-house gases (Raupach et al., 2007). Agricultural production, and thus global food security, is directly affected by global warming (Fischer et al., 2005; Schmidhuber and Tubiello, 2007; Ainsworth and Ort, 2010). Temperature controls the rate of plant metabolic processes that ultimately influence the production of biomass, fruits and grains (Hay and Walker, 1989). By 2080, most cropping areas in the world are likely to be exposed to record average air temperatures (Battisti and Naylor, 2009). High average "seasonal" temperatures can increase the risk of drought, limit photosynthesis rates and reduce light interception by accelerating phenological development (Tubiello et al., 2007). Previous global food assessments have shown that these negative effects are particularly exacerbated in tropical regions (IPCC, 2007a; Fischer et al., 2005). On the other hand, these negative impacts of higher seasonal temperatures are less pronounced in temperate regions where global warming may increase the length of the growing period and may render land suitable for cropping where low temperatures used to limit agriculture (Olesen and Bindi, 2002). However, previous studies have not taken into account the effect of short occurrences of extremely high temperatures, or "heat stress" events. Heat waves are likely to become more frequent with global warming (Tebaldi et al., 2006; IPCC, 2007b). In 2010, when more than 20% of Russian agricultural producing areas were affected by unprecedented extreme high temperatures, wheat prices increased by up to 50% in the international market (FAO, 2010; NOAA, 2011b). Peaks of high temperature, even when occurring for just a few hours, can drastically reduce the

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production of important food crops (Porter and Semenov, 2005; Prasad et al., 2000). Heat stress damage is particularly severe when high temperatures occur concomitantly with critical crop development stages, particularly the reproductive period. Because of this, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has acknowledged heat stress as an important threat to global food supply (IPCC, 2007b). Currently, there is a lack of understanding on the spatial distribution and intensity of crop damage caused by heat stress. Spatially, heat stress damage is expected to vary with climate, land suitability for production and the sensitivity of cultivated crops. Temporally, the choice of crop calendars (i.e. time of sowing and harvesting) and the rate of crop development influence the exposure to extreme temperatures during critical phenological phases. To assess heat stress risk, it is then necessary to take into account the timing, frequency and extent by which crop-specific temperature thresholds are exceeded during critical crop development stages.

In this study, we performed a spatially explicit assessment of heat stress at the global scale, considering these environmental and management aspects, to identify hot-spots of risk for four important food crops (wheat, rice, maize and soybean). We used the Global Agro-Ecological Zones Model (GAEZ v3.0) to simulate the risk of heat stress for these four crops for a 30-year baseline historical climate (1971–2000) and an alternative future climate scenario (2071–2100) considering climate change.

2. Modeling methodology

2.1. Climate scenarios

Global 1.125° gridded datasets of daily maximum and minimum temperatures (°C; T_{max} and T_{min}, respectively) from the Global Circulation Model (GCM) at the National Institute for Environmental Studies (NIES; Ibaraki, Japan; www.nies.go.jp/index.html) were used for simulations. This GCM was chosen because of the high temporal resolution of climate data provided (i.e. daily fields of T_{max} and T_{min}) which is required to assess the impact of extreme events. In contrast, available GCM outputs are mainly for monthly climate data which are less suitable for studying impacts of extreme temperature episodes, as extreme daily temperatures are smoothed. Simulations comprised two climate scenarios: (i) baseline climate for 1971–2000 and (ii) future climate for the time-period from 2071 to 2100 using the A1B emissions scenario of the Intergovernmental Panel on Climate Change (IPCC, http://www.ipcc.ch/). In brief, the A1 storyline describes: "...a future world of very rapid economic growth, global population that peaks in the mid-century and declines thereafter, and a rapid introduction of new and more efficient technologies. Major underlying themes are technological/economical convergence among global regions, increased capacity building and socio-cultural interactions, with a substantial reduction in regional differences in per capita income. The subgroup A1B is characterized by its technological emphasis: fossil intensive and non-fossil energy sources are balanced, therefore there is not a heavy dependence on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies" (IPCC, 2000). This scenario was chosen for the present study because, among the available IPCC scenarios, it represents a "mid-range" in green-house gas emissions.

2.2. Simulation of crop distribution, cropping calendars and yields

The modeling exercise considered four agricultural crops: maize (*Zea mays*), rice (*Oriza sativa*), soybean (*Glycine max*) and wheat (*Triticum aestivum*). Both winter and spring wheat were considered in simulations. These four crops were selected because of their high significance for global food supply; together they account for more than 40% of human calorie intake and ~650 Mha or 45% of global cultivated crop land (FAOSTAT, 2009a).

Table 1
Details of each crop and land utilization types (LUT) used in the simulations.

Crop species	Number of land utilization types (LUT) tested per crop species	Range in crop cycles (days) for the tested LUTs
Maize (*Zea mays*)	24	90–300
Wetland rice (*Oriza sativa*)	8	105–150
Soybean (*Glycine max*)	6	105–135
Wheat (*Triticum aestivum*)	20	90–190

The simulation of crop distribution, cropping calendars and potential yields for the four selected crops (Table 1) was performed at a 1.125° spatial resolution (~140 km at the equator) using the FAO/IIASA Global Agro-Ecological Zones (GAEZ) model (Fischer et al., 2002). The presence of a crop in a given grid cell was evaluated by matching the physiological requirements of each GAEZ 'land utilization type' (LUT) with the prevailing average climatic condition of each simulation scenario. The LUT concept characterizes different crop sub-types within a crop species, including differences in crop cycle length (i.e. days from sowing to harvest), growth and development rates in response to environmental drivers (Fischer et al., 2002). GIS layers of land cover, slope and terrain (i.e. GAEZ land resources datasets) and yield simulations were used to identify the suitability for agricultural production in each grid cell. The potentially suitable land estimated for a given crop generally exceeds its current harvested area because it represents the extents and distribution of land where crops could be cultivated without considering economic factors or agro-edaphic limitations. In the GAEZ model, agro-climatic potential yields are mainly determined by the availability of solar radiation and seasonal temperature, while attainable rain-fed yields are further limited by water availability, soil characteristics and terrain slopes (Fischer et al., 2002). To ensure the assessment of heat stress occurred only in areas suitable for agriculture, grid cells were only considered when attainable yields were ≥20% of potential yields and at least 5% of the land in a grid cell was indicated as cultivated in year 2000. For each climate scenario and crop species, the "optimal crop calendar" and the "highest-yielding LUT" were determined by simulating yields for all possible "LUT/sowing date" combinations and then selecting the highest yield in each grid cell for the average climate from each 30-years climate scenario. For wheat, maize and soybean, we considered only rain-fed conditions in which the date of crop sowing is highly dependent on sufficient soil moisture available for allowing seed germination and seedling establishment. Both winter and spring wheat types were tested in each grid cell and the highest yielding crop type was selected. For wetland rice, we considered a sowing calendar for irrigated crops because rice worldwide is mostly cultivated under irrigated conditions (FAOSTAT, 2009b). Weather datasets used in GAEZ for this analysis were from the NIES-GCM (Section 2.1).

2.3. Modeling the risk of heat stress damage

The physiological patterns of response to heat stress seem to be consistent among different crop species. For example, heat stress reduces the number of flowers/plant, impairs pollen tube development, limits pollen release and diminishes both pollen viability and flower fertility (Gross and Kigel, 1994; Matsui et al., 2000; Prasad et al., 2000, 2006a; Suzuki et al., 2002). In contrast, the threshold temperature above which heat stress responses resume differs among species and cultivars. As temperatures rise above these critical thresholds, the relative intensity of yield-damage increases

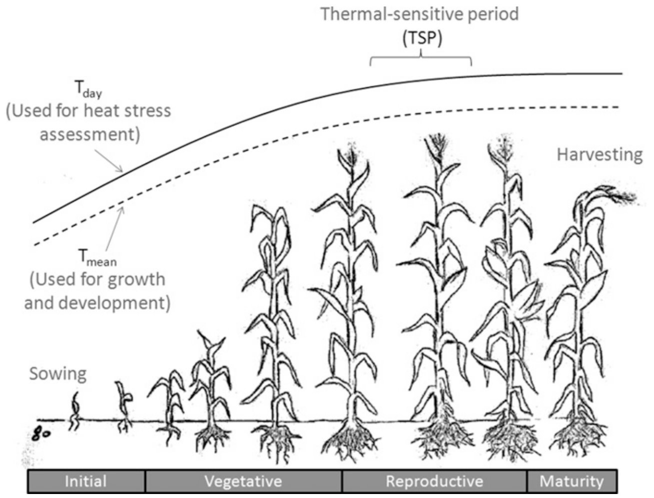

Fig. 1. Schematic representation of the development stages in the GAEZ model and the allocation of the thermal-sensitive period in the mid-point of the reproductive period. TSP is the thermal-sensitive period (days) when heat stress impact is calculated, T_{day} is the daytime temperature and T_{mean} is the daily average temperature.

until total yield loss is reached. In absolute terms, losses are potentially higher in more productive cropping systems. Therefore, our rationale to assess heat stress risk includes three dimensions: (i) the frequency of occurrence of high temperatures during sensitive periods, (ii) the intensity of high temperatures in relation to crop-specific thresholds and (iii) the expected production of the affected crop in each grid cell.

2.3.1. Heat stress intensity index (f_{HS})

The heat stress intensity index (f_{HS}, fractional), calculated for each grid cell/crop/year combination, was based on the framework developed by Challinor et al. (2005). The main principles underlying this methodology are that (i) crops are only sensitive to heat stress during the reproductive phase of development, here named the thermal-sensitive period (TSP, days); (ii) yield-damage resumes when daytime temperatures (T_{day}, °C) exceed a critical temperature threshold (T_{crit}, °C); and maximum impact occurs when T_{day} exceeds the limit temperature threshold (T_{lim}, °C). We have opted to use T_{day}, instead of maximum temperature (T_{max}), because T_{day} might more closely represent the temperature experienced by the crop during flowering. For example, some rice cultivars open their flowers early in the morning therefore avoiding exposure to maximum temperatures (Wassmann et al., 2009a). Although TSP is likely to differ with species and cultivar, we have assumed a constant TSP of 30 days centered in the mid-point of the reproductive phase (Fig. 1). A sensitivity analysis varying TSP from 6 to 30 days indicated that broad-scale spatial patterns of heat stress were only slighted affected (data not shown). This simplification aimed to conservatively cover the most critical periods reported in the literature for different species (e.g. Suzuki et al., 2002; Wheeler et al., 2000; Porter and Gawith, 1999; Lobell et al., 2011; Ferris et al., 1998).

Temperature thresholds (T_{crit} and T_{lim}) are not sufficiently defined for different cultivars to enable a cultivar-specific parameterization at global scale. We therefore consider approximate parameter values (based on T_{day}) for each species (Table 2) taking in consideration current literature and previous modeling exercises for rice (Prasad et al., 2006b; Wassmann et al., 2009a), maize (Lobell et al., 2011; Schlenker and Roberts, 2009), wheat (Semenov and Shewry, 2010; Porter and Gawith, 1999) and soybean (Salem et al., 2007).

To calculate f_{HS}, we initially estimate the "daily" heat stress intensity (f_{HSd}) as a function of T_{day}. The value of f_{HSd} is a surrogate

Table 2
Parameterization used for the heat-stress assessment.

Crop species	T_{crit} (°C)	T_{lim} (°C)
Maize (*Zea mays*)	35	45
Wetland rice (*Oriza sativa*)	35	45
Soybean (*Glycine max*)	35	40
Wheat (*Triticum aestivum*)	27	40

for yield-damage intensity due to heat stress and is assumed to increase linearly from 0.0 at T_{crit} to a maximum of 1.0 at T_{lim} (Eq. (1)).

$$f_{HSd} = \begin{cases} 0.0 & \text{for } T_{day} < T_{crit} \\ \dfrac{T_{day} - T_{crit}}{T_{lim} - T_{crit}} & \text{for } T_{crit} \leq T_{day} < T_{lim} \\ 1.0 & \text{for } T_{day} \geq T_{lim} \end{cases} \quad (1)$$

The daily values of f_{HSd} are then accumulated and averaged throughout the thermal-sensitive period (TSP) to calculate the heat stress intensity index (f_{HS}) for the entire TSP (Eq. (2)).

$$f_{HS} = \frac{\sum_{j=1}^{TSP}(f_{HSd})}{TSP} \quad (2)$$

Therefore, the value of f_{HS} reflects both the intensity and the number of heat stress events experienced during the sensitive period of crop growth.

2.3.2. Normalized production damage index (f_{dmg})

In addition, we calculated the production-damage index (f_{dmg}) which is a proxy for the magnitude of produce losses caused by heat stress, given the inherent agricultural production expected in grid cells identified as "suitable" by GAEZ for each crop. Crop attainable production (P_{att}; kg/grid cell) is calculated by GAEZ as the product of crop yield (kg produce/ha), grid cell size (ha) and share of cultivated area (fractional). The f_{dmg} is calculated for each year as the product of the f_{HS} index (Section 2.3.1) and P_{att} for each grid cell and then accumulated for all grid cells in the region of interest. The result is normalized by the maximum annual value of f_{dmg} ($f_{dmg_{max}}$) predicted in the 30-year simulation (Eq. (3)). This procedure allows the comparison of "relative" magnitude and annual variability of impact to production between the baseline and the A1B climate scenarios for each crop species within a region of interest.

$$f_{dmg_n} = \frac{\sum_{i=1}^{z}(P_{att} \times f_{HS})}{f_{dmg_{max}}} \quad (3)$$

where f_{dmg_n} is the normalized value of damage index, $f_{dmg_{max}}$ is the maximum annual value of f_{dmg} during the 30-year simulation.

3. Results

3.1. Intensity of heat stress

There was a consistent increase in the maximum intensity of heat stress (f_{HS} index), predicted for a 30-year period, from the baseline climate (Base, 1971–2000) to the future climate change scenario (A1B, 2071–2100) for all crops in large areas (Fig. 2). The main hot-spots of heat stress occurred in the continental parts of Central Asia (e.g. Russian Federation and Kazakhstan), East Asia (e.g. North-Eastern China), South Asia (e.g. Northern India) and North America.

Wetland rice showed high heat stress intensity already for the Base climate (1971–2000), particularly in South Asia. For this crop, the highest increases in heat stress intensity for A1B occurred in suitable areas of Central and Eastern Asia, Southern Australia, Central North America, and South East Brazil.

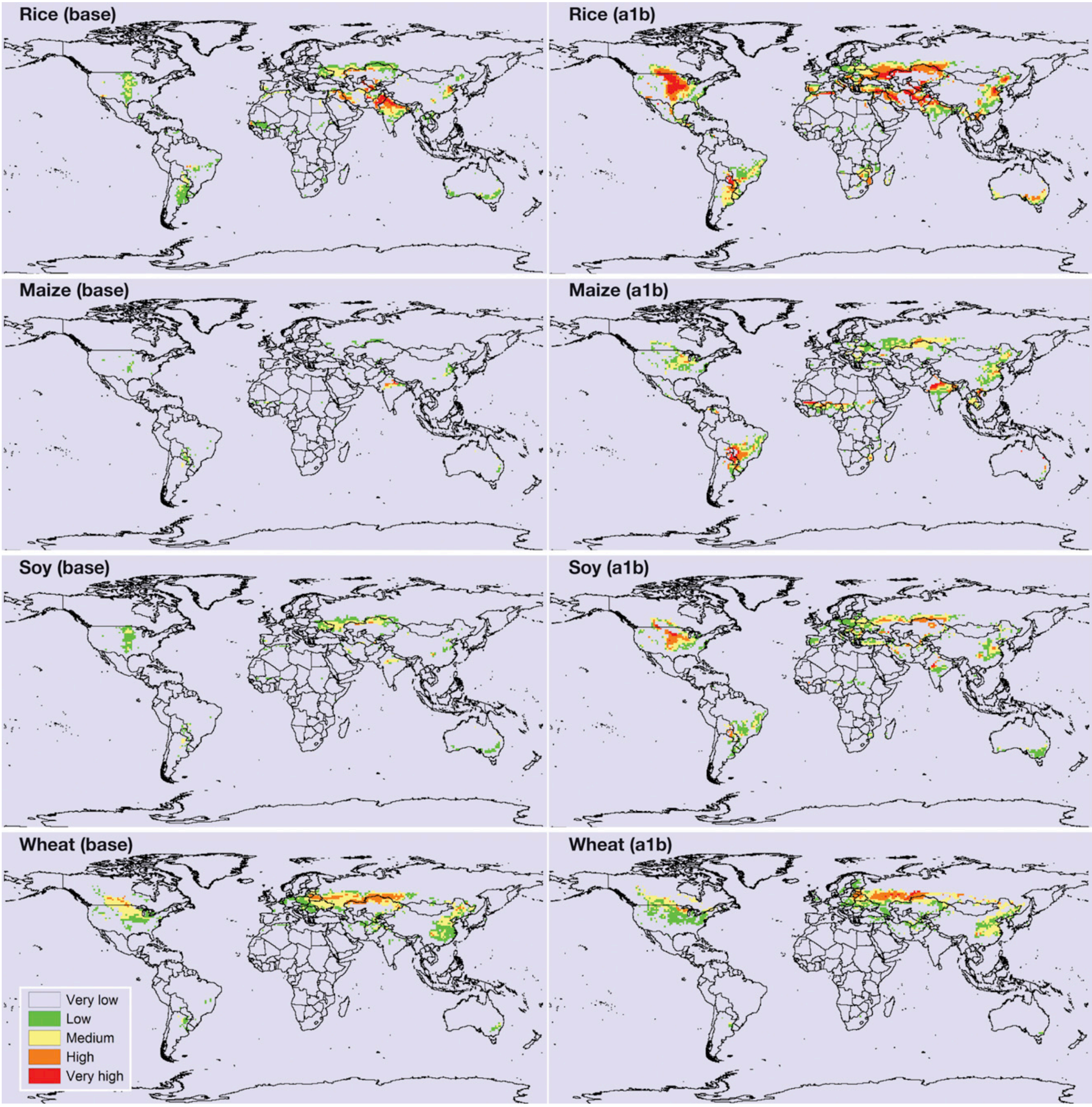

Fig. 2. The maximum heat stress intensity within a 30-year simulation in areas suitable for the production of rain-fed wheat, maize and soybean and for wetland rice for the baseline climate (Base, 1971–2000) and the A1B climate change scenario (2071–2100). Heat stress categories are very low stress (unsuitable land or $f_{HS} = 0.0$), low ($f_{HS} < 0.05$); medium ($0.05 \leq f_{HS} < 0.15$); high ($0.15 \leq f_{HS} \leq 0.30$); and very high ($f_{HS} > 0.30$) stress intensity.

In contrast, only little heat stress was predicted for maize under the Base climate but the intensity increased to median levels under A1B. Northern India, the Sahel region, South East Africa and Central South America were hot spots of heat stress for maize.

A moderate heat stress intensity was predicted for soybean for the Base climate (mainly in Central Asia and Northern India) with a considerable increase in intensity and extension for A1B, with new areas under stress in Central North America and Central Brazil.

For wheat, heat stress intensity was most intense throughout Central Asia mainly at the border between Russian Federation and Kazakhstan, stretching from Eastern Europe to Northern China. Compared with the other crops, there was less change in spatial pattern and intensity of heat stress from the Base to the A1B scenario.

The absolute difference in the maximum intensity of heat stress (f_{HS} index) from the baseline to the A1B scenario is shown in Fig. 3.

3.2. Frequency of heat stress events

The percentage of days, within a 30-year period, with heat stress events (i.e. $T_{day} > T_{crit}$) increased from the Base to the A1B climate scenario (Fig. 4). This increase was most evident for wetland rice in suitable areas of Central Asia, South Asia and Central North America where a high prevalence was predicted. On the other hand, wheat had a less pronounced change in the frequency of stress in A1B with less than 20% prevalence in most affected areas.

3.3. Land area affected by heat stress

Most affected lands were located in continental regions at mid to high latitudes, particularly in the Northern Hemisphere (Fig. 5). The largest extension of land at risk was predicted to occur between

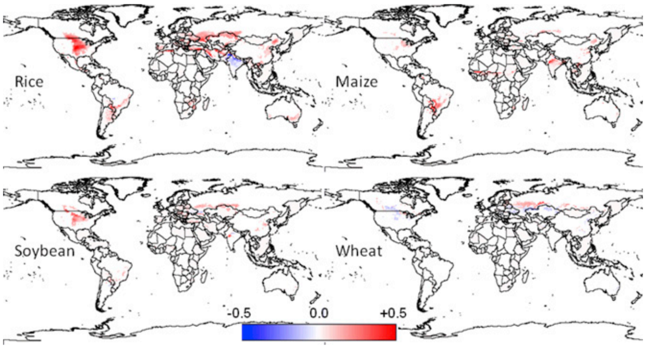

Fig. 3. The difference between the baseline climate (Base, 1971–2000) and the A1B climate change scenario (2071–2100) for the maximum heat stress intensity within a 30-year simulation in areas suitable for the production of rain-fed wheat, maize and soybean and wetland rice.

40 and 60°N. A maximum range between 6 and 10 Mha of suitable land at risk (for each 1.125° latitudinal band) was estimated in this latitudinal range. In comparison, negligible heat stress effects were simulated for equatorial regions (20°S to 20°N). There was a large inter-annual variability in the area affected by heat stress, as shown by the different ranges between the 25th and 75th percentiles, depending on crop type and climate scenario. Affected areas for wetland rice and soybean (Fig. 5b and f) were predicted to be less variable than for maize and wheat (Fig. 5d and h) in A1B.

As a result, the area of global suitable land affected by heat stress increased in A1B for most crops, with the exception of wheat (Fig. 6). Wetland rice showed the largest areas at risk which increased from a median of 57 Mha for the Base climate to 121 Mha for A1B.

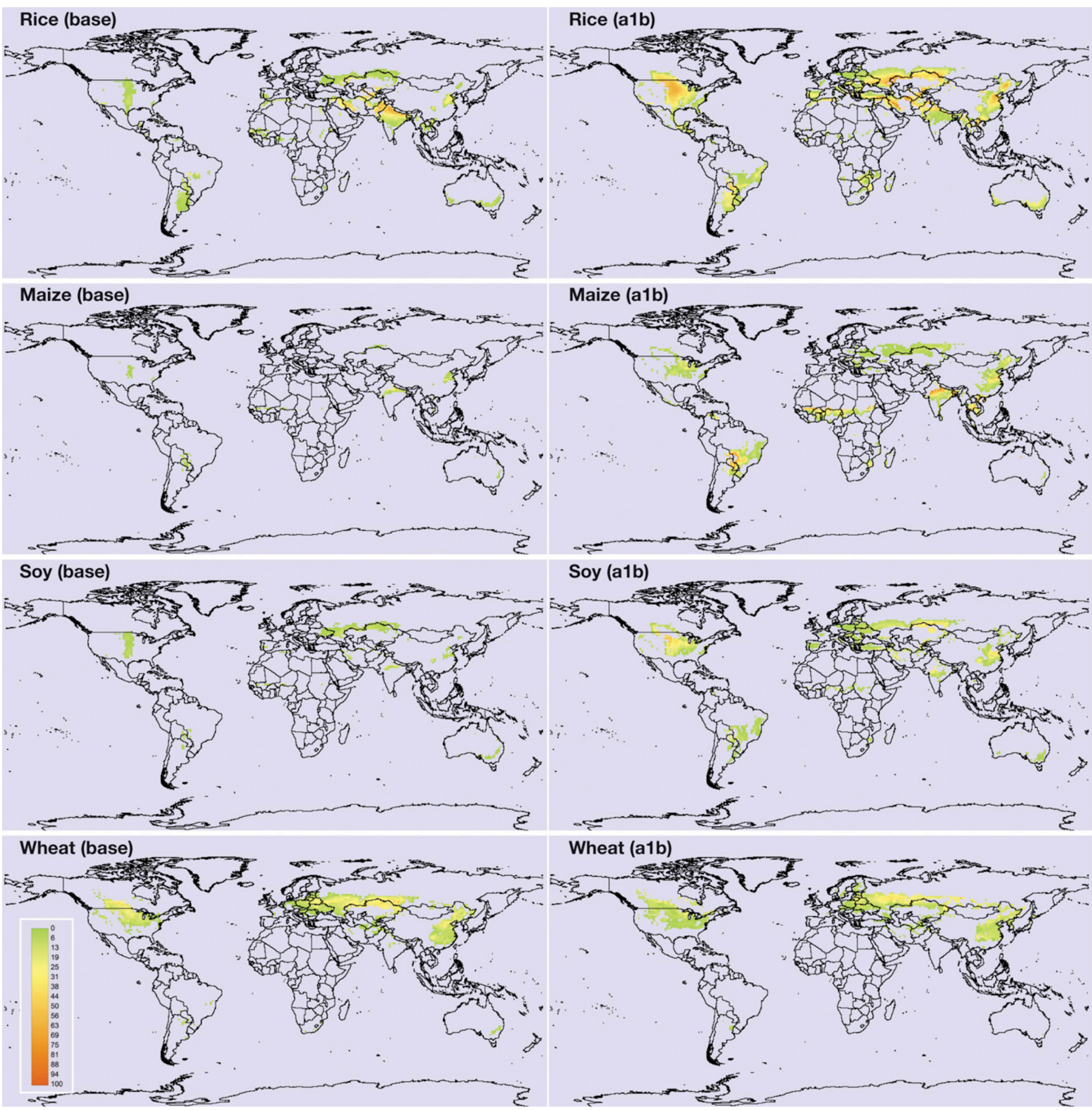

Fig. 4. The percentage of days with heat stress events within the thermal sensitive period for a 30-year period simulation for the baseline climate (Base, 1971–2000) and the A1B climate change scenario (2071–2100) for the production of rain-fed wheat, maize and soybean and wetland rice.

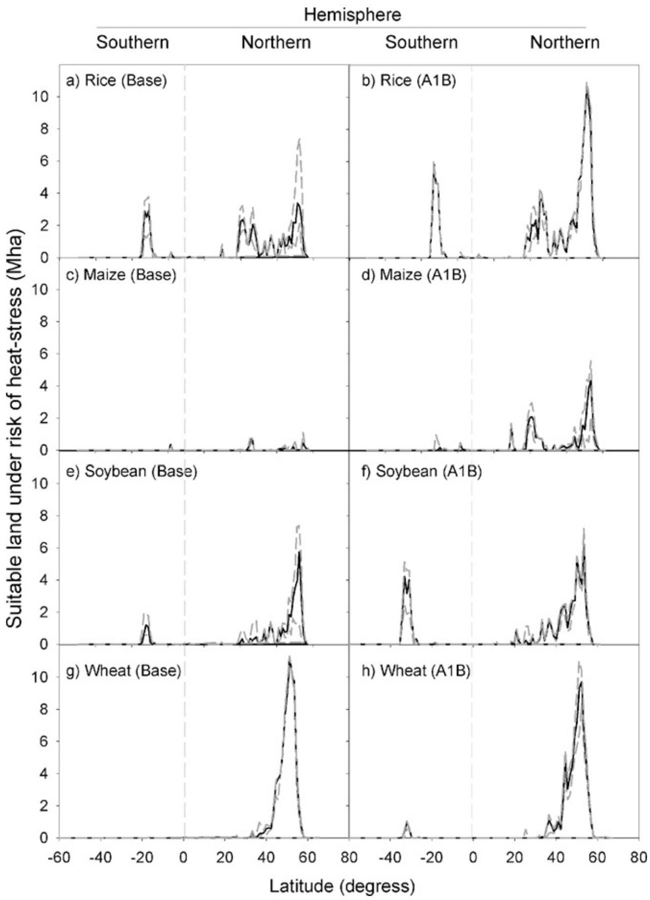

Fig. 5. Area under risk of heat stress (Mha) for each 1.125° latitudinal-band in a 30-year analysis period for four different crops for the baseline climate from 1971–2000 (Base) and the future climate change scenario (A1B) for 2071–2100. Solid line indicates median value and dotted lines indicate 25th and 75th percentile.

3.4. Normalized production damage index

3.4.1. Global damage

Relative production damage to wetland rice, maize and soybean increased for the A1B climate scenario, in agreement with increases

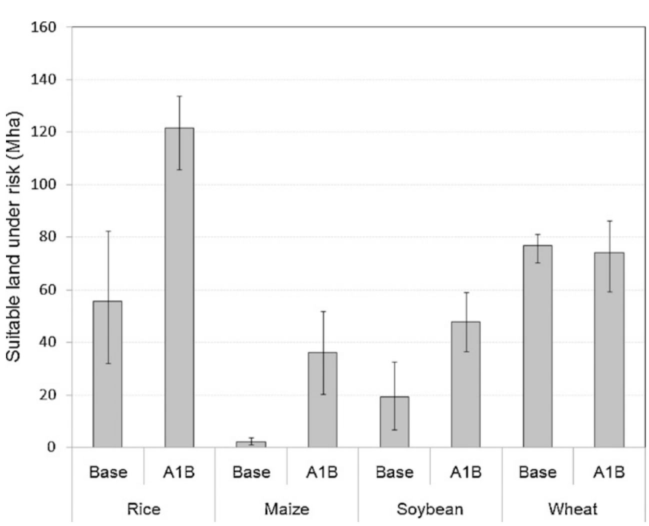

Fig. 6. Global suitable land area under risk of heat stress for four different crops for the baseline climate (Base; 1971–2000) and the future climate change scenario (A1B; 2071–2100). Columns indicate the median value and error bars show variation range from 25th to 75th percentile for the 30-year analysis period.

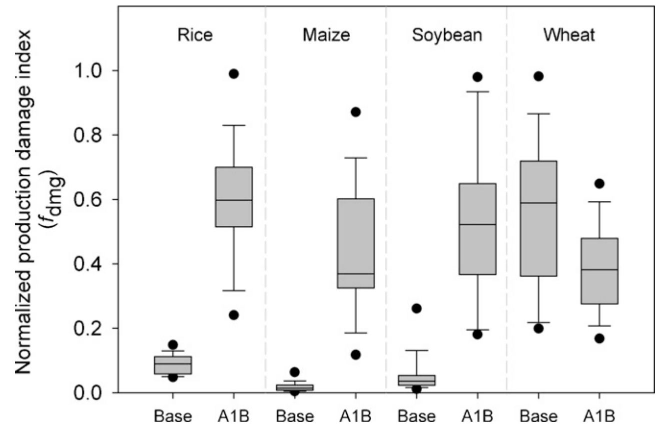

Fig. 7. Relative change in the normalized production damage index (f_{dmg}) from the baseline climate (Base; 1971–2000) to the future climate change scenario (A1B; 2071–2100) for different crops. Values are normalized by the maximum annual f_{dmg} estimated for each crop. Solid horizontal line inside boxes indicates the median value for the 30-year analysis period, box-boundaries are the 25th and 75th percentiles, whiskers are the 10th and 90th percentile and dots indicate 5th and 95th percentile.

in intensity (Section 3.1) and frequency (Section 3.2) of heat events for these crops (Fig. 7). In contrast, relative damage to rain-fed wheat was reduced in A1B. This decline was mainly caused by the changes in the selected LUTs and sowing dates for A1B by GAEZ, which produced new combinations of attainable yields, intensity and frequency of heat stress at the individual grid cell level.

3.4.2. Production damage for selected global regions

The relative changes in potential damage and its inter-annual variability, within geographic regions, differed with crop species and regions (Fig. 8). As an example, results are aggregated for four important global agricultural regions, namely: (i) Central Asia plus Russian Federation; (ii) South Asia plus East Asia; (iii) North America and; (iv) South America. The highest relative increases in production damage from the baseline climate to A1B were predicted for soybean and maize throughout all regions (Fig. 8b and c). Inter-annual variability also increased for most crop/region combinations in A1B. An increase in relative damage to wheat was most evident in South Asia plus East Asia, largely driven by the expansion in affected areas in this region (Fig. 2) as opposed to a reduction for Central Asia plus Russian Federation and small changes for North America (Fig. 8d).

4. Discussion

Global hot spots of crop heat stress overlap with important agricultural regions such as Eastern China, the Northern United States, South-Western Russian Federation and Southern Canada (Fig. 2). This indicates that agricultural production in temperate countries may suffer substantial production losses from climate change (as for the A1B emission scenario used in our study), extending the findings of previous studies that impacts would mainly occur in sub-tropical and tropical regions (IPCC, 2007a; Fischer et al., 2002, 2005).

Overall, our results suggest that heat stress imposes an increasing risk to agricultural production, particularly in continental areas at mid and high Northern latitudes (Fig. 5). Average multi-model projections by the IPCC have shown larger temperature increases in temperate areas (IPCC, 2007b) which, together with higher temperature variability, substantially increases the risk of heat stress in these regions. Heat stress adds to other important effects of global warming on crop growth and development. The increase in crop water demand (due to increase in evapo-transpiration), the acceleration of crop development (i.e. shortening of crop cycles),

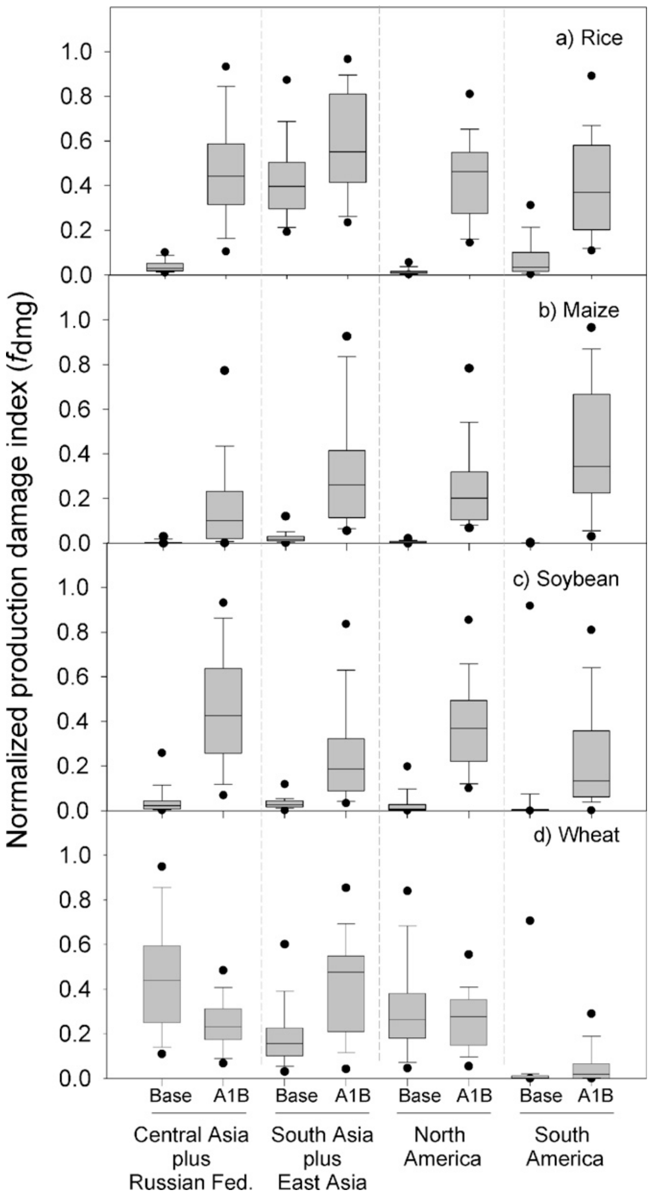

Fig. 8. Relative change in the normalized production damage index (f_{dmg}) from the baseline climate (Base, 1971–2000) to the future climate change scenario (A1B, for 2071–2100) for four aggregated global regions, considering four different crops. Values are normalized by the maximum annual f_{dmg} for a given crop within each region. Solid horizontal line inside boxes indicates the median value for the 30-year analysis period, box-boundaries are the 25th and 75th percentiles, whiskers are the 10th and 90th percentile and dots indicate 5th and 95th percentile.

and an increase in night respiration are examples of impacts in both tropical and temperate regions (Tubiello et al., 2007). The A1B climate scenario, used in this study, is intermediate in terms of equivalent CO_2 emissions and consequent global warming (IPCC, 2007b) and may underestimate the warming trend in these regions. In the last decade, several high latitude regions of the Northern Hemisphere have in fact experienced the warmest above-average annual temperatures on record (NOAA, 2011a).

4.1. Limitations on global estimations of crop heat stress

Our global analysis provides a first base for identification of major spatial patterns of crop heat stress at broad-scale. The estimation of crop heat stress was done by systematically segmenting risk into different components, namely (i) the intensity of heat stress episodes (Section 3.1); (ii) the frequency of heat stress episodes (Section 3.2); and (iii) the attainable production at risk in a grid cell (Section 3.3). For that, a methodology with simplified parameterization, consistent with the spatial–temporal resolution of the GAEZ model and the NIES-GCM dataset, was used. The resulting broad-scale analysis is suited to capturing major spatial patterns at global level but should not be interpreted at a fine regional scale due to large uncertainties in the grid cell level. Numerous factors not considered here are expected to influence the impacts of and resilience to heat stress at a local scale such as micro-climate, soil characteristics, socio-economic conditions, available technology and infrastructure. For example, in multi-cropping production regions such as the Indo-Gangetic plain, which was identified as a hot-spot of heat stress for maize and wetland rice (Figs. 2 and 4), the long length of the growing period and water availability allows sequential crops to be sown within 1 year (Panigrahy et al., 2010). Under these conditions, the impact of heat stress in one crop may be diluted by the overall annual production. Using actual crop calendars for rice in Asia, Wassmann et al. (2009b) characterized heat stress prone areas in continental Southeast Asia and southern and western parts of the Indian subcontinent which were not all evident in our large area assessment.

To further explore regional impacts and adaptation options (Section 4.3), better accounting for existing uncertainties, it is therefore necessary to perform assessments at finer spatial scales and use more mechanistic modeling procedures (e.g. Challinor et al., 2007) than the ones applied in our study. Future work may include consideration of climate variability (e.g. Semenov, 2007), the use of a suite of different Global Circulation Models (e.g. Semenov and Shewry, 2010) and climate scenarios, cultivar specific temperature thresholds, the occurrence of multi-cropping and the effect of adaptation such as the change in crop calendars (e.g. Teixeira et al., 2011).

4.2. Regional and crop differences in heat stress responses

Overall, most lands under high risk of heat stress were located in regions with continental climate at sub-tropical and temperate latitudes (Fig. 5). At higher latitudes, the time window for sowing is reduced because day length and cold temperatures constrain seed germination and plant development in winter and part of autumn and spring (Hay and Walker, 1989; Hodges, 1991). As a consequence, the optimum crop calendar tends to overlap with the warmest periods in summer, increasing the probability of exposing plants to extreme temperatures during the onset of flowering. This effect is exacerbated in continental areas, such as Central Asia and Central North America (Fig. 2), where temperatures are less influenced by oceanic winds and air masses that insulate and moderate extreme summer temperatures in coastal lands (Grieser et al., 2006; Driscoll and Fong, 1994). After incoming solar radiation, continentality is the main factor controlling variation in land surface temperature and defining local temperature range (Driscoll and Fong, 1994). In general terms, the continentality index is closely related with a location's distance to the sea (Grieser et al., 2006) but other factors such as land relief, prevailing wind direction and volume of nearby water bodies also modulate the overall continentality effect, influencing temperature variation at regional level (Driscoll and Fong, 1994) and consequently heat stress risk. The flexibility of shifting sowing dates so as to avoiding heat stress depends on the balance between the increases in the length of the growing period (in response to seasonal average temperatures and precipitation) and the increases in the frequency and intensity of extreme temperature events.

The impact of heat stress largely differed with crop type. Wetland rice was the crop with the most intensely affected areas (Fig. 2). The use of irrigation allows growers to cultivate in periods of high incoming radiation and optimal seasonal temperatures that, historically, have maximized yield. However, with the increase in the frequency of extreme temperature events, climate change may enhance the probability of overlapping peaks of temperature and the flowering period. Even if radiation interception and photosynthesis are increased under these conditions, heat stress reduces final yields by different physiological mechanisms that limit formation of plant sinks for photosynthates (e.g. grains). The prediction of high risk for rice crops, already for the baseline climate (Figs. 2 and 4), agrees with recent reports indicating that at least six severe heat events damaged crops in the past 50 years in China (Tian et al., 2009). In 2003, approximately 3 million hectares were affected with an estimated loss of about 5.18 Mt of grain in the Yangtze River Valley alone. On the other hand, our results for wetland rice may overestimate the actual temperature experienced by crops in dry environments. Crops grown in environments with high vapor pressure deficit and with ample supply of water through irrigation maintain lower canopy temperature due to leaf transpirational cooling, which reduces the risk of heat stress (e.g. Matsui et al., 2007). Irrigation amounts and scheduling may therefore influence the risk of heat stress damage (van der Velde et al., 2010).

Results for rain-fed maize and soybean crops followed a similar pattern of having small areas under risk for the baseline climate but showing a large increase in both area and intensity of heat stress for A1B (Fig. 7). For maize, high heat stress impacts were predicted in the Sahel and South-Eastern African regions (Fig. 2). This extends the recent findings by Lobell et al. (2011) who, based on the reanalysis of more than 20,000 experiments in sub-Saharan Africa, estimated that for each extra one degree-day accumulation above a base temperature of 30 °C there was an 1% decline in maize yield.

By contrast, a regional reduction in impact was observed for rice in the North of India and wheat in North America and Asia (Fig. 3). For wheat, this caused a 35% reduction in global damage for A1B (Fig. 7) which was partially explained by the 4% decline in affected areas (Fig. 6). However, most of the difference came from the new spatial pattern of LUT allocation (with different cycle lengths and yields) and sowing dates selected by GAEZ in response to seasonal climate (e.g. average temperatures). This caused a consequent shift of the TSP, potentially affecting the intensity and frequency of heat stress. Changes in crop management, through the choice of genotypes with contrasting cycle lengths and the use of different sowing dates, may provide a viable option to mitigate heat stress impacts as recently suggested by Deryng et al. (2011) and indicated by our results for wheat and rice (Fig. 3).

The analysis of regional differences in damage may be more informative than the aggregated global figures. In South Asia plus East Asia, wheat damage has increased by twofold for A1B (Fig. 8). This agrees with regional assessments using process-based crop models that have projected consistent impacts of warm temperatures on wheat yields at different locations in Europe and Australia (Asseng et al., 2011; Semenov and Shewry, 2010). The need to develop adaptive measures for wheat production grown under warmer conditions has been previously highlighted by Ortiz et al. (2008). For example, Biswas et al. (2008) suggested that in monsoon regions, where rice–wheat crop rotations are common, heat stress could be mitigated by introducing minimum-tillage which allows wheat to emerge earlier and avoid the overlapping of the reproductive stage with the warmest periods. In our study, GAEZ simulates optimum crop calendars that may differ from actual crop calendars for reasons of location specific annual crop combinations or socio-economic factors (e.g. marketability). Given the uncertainties inherent to broad-scale modeling studies (Challinor, 2011; see Session 4.1), the effectiveness of adapting sowing dates and crop types must be validated at local level (Section 4.3).

4.3. Considerations on policy implications and adaptation to heat stress

Given that historical emissions have created a commitment for further future changes of the climate system (IPCC, 2007b) and given the increasing rates of current emissions (Raupach et al., 2007), adaptation of agricultural practices becomes critical to cope with inevitable global warming (Howden et al., 2007). The infrastructure and technological resources already in place will largely influence the effectiveness of adaptation to a warmer environment (Reidsma et al., 2010).

For European conditions, Olesen et al. (2011) identified the change in crop calendars and the selection and breeding of more resilient genotypes as the main adaptive solutions expected to reduce climate change impacts on agriculture. These authors also highlight the importance of increasing use of water-conserving practices (e.g. minimum tillage), seasonal forecasting and crop insurance schemes.

Differences in spatial patterns of heat stress intensity (Fig. 2), frequency (Fig. 4) and in the relative change from the baseline to the A1B future climate (Fig. 8) indicate the importance of searching for adaptive technologies at local level. In fact, adaptive decisions ought to occur at the farm level in response to local conditions (Reidsma et al., 2009), which makes it impossible to prescribe a single strategy at global level. The ability to adapt agricultural practices is also strongly influenced by social and economic factors. Farmers who have been historically exposed to variable climatic conditions, such as in the Mediterranean region, tend to be more prepared to cope with climatic change (Reidsma et al., 2009). Solutions to cope with heat stress will need to be tailored to the reality of each specific agricultural production system under risk.

Some adaptation options are crop-specific. Wetland rice, a largely impacted crop (Fig. 6), shows a wide genetic variability for resistance to heat stress (Prasad et al., 2006b; Matsui and Omasa, 2002). This potential could be explored to screen rice germplasm and select cultivars that open flowers earlier in the morning (avoiding warmest hours of the day) or that maintain a high number of spikelets/panicle when grown in warm environments (Prasad et al., 2006b; Singh et al., 2010; Matsui et al., 2000; Jagadish et al., 2007). Selection for rice genotypes with differential canopy architecture to enable cooling of reproductive organs through plant transpiration, has also been suggested as a possible strategy (Wassmann et al., 2009a). A lot of expectation has been put on molecular biology as the novel agricultural research tool to identify molecular markers associated with stress related plant traits, as well as individual candidate genes for stress tolerance (Barnabas et al., 2008). Nevertheless, its effectiveness to provide short-term solutions for heat stress tolerance is unknown due to the complexity of the genetic background for desirable physiological traits and their interaction with the environment (Slafer, 2010). The use of mathematical modeling in conjunction with genetic information is emerging as an additional methodology to assist the identification of physiological traits for new plant ideotypes (Semenov and Halford, 2009).

Investment in policies and international collaborative efforts to spatially quantify and better understand effects of heat stress is necessary. For example, the “Multilateral Research Exchange Project for Securing Food and Agriculture” (Yoshimoto et al., 2009), has set a global multi-site network to monitor micro-meteorological conditions at canopy level to characterize heat stress in rice fields at costal and continental regions, with prospects to be enhanced in the future (Yoshimoto et al., 2010). Similarly, research to develop new management options and genotypes adapted to a warmer environment was initiated both at the International Maize and Wheat Improvement Center (CIMMYT) (Ortiz et al., 2008) and at the International Rice Research Institute IRRI (Wassmann and Dobermann, 2007).

In summary, our results reinforce the urgent need to plan adaptive strategies for agriculture with regard to heat stress. Investments to support research to better understand plant physiological responses to stress and to develop adaptation options are vital to prepare current agricultural production systems for a warmer environment (Ainsworth and Ort, 2010; Challinor, 2011). It is of great concern that the rate of growth in investment on global agricultural R&D, essential to explore adaptive strategies (Ingram et al., 2008), has been declining over the past decade (Beintema and Elliott, 2009). Technically, adaptation seems possible, as there is a wide genetic variability for tolerance to high temperatures within and among plant species (Wahid et al., 2007). The adaptation of agricultural practices *per se*, such as shifting sowing time, changing cultivars and land use options, should also be explored as regional strategies to minimize the overall impact of global warming on food production.

5. Conclusions

Extending the findings of previous studies which concluded that mainly tropical agriculture will suffer from climate change, our results indicate that global food supply may also be affected by heat stress in temperate and sub-tropical regions. Without mitigation measures to combat climate change or the implementation of local adaptive technologies, countries with extensive agricultural lands in continental regions at high latitudes may experience significant crop losses. Investment in local adaptive measures such as development of resistant varieties and changes in crop management are therefore necessary to minimize risks to global food supply.

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