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Estimating crop yield potential at regional to national scales

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ABSTRACT

World population will increase 35% by 2050, which may require doubling crop yields on existing farm land to minimize expansion of agriculture into remaining rainforests, wetlands, and grasslands. Whether this is possible depends on closing the gap between yield potential (Yp, yield without pest, disease, nutrient or water stresses, or Yw under water-limited rainfed conditions) and current average farm yields in both developed and developing countries. Quantifying the yield gap is therefore essential to inform policies and prioritize research to achieve food security without environmental degradation. Previous attempts to estimate Yp and Yw at a global level have been too coarse, general, and opaque. Our purpose was to develop a protocol to overcome these limitations based on examples for irrigated rice in China, irrigated and rainfed maize in the USA, and rainfed wheat in Germany. Sensitivity analysis of simulated Yp or Yw found that robust estimates required specific information on crop management, +15 years of observed daily climate data from weather stations in major crop production zones, and coverage of 40–50% of total national production area. National Yp estimates were weighted by potential production within 100-km of reference weather stations. This protocol is appropriate for countries in which crops are mostly grown in landscapes with relatively homogenous topography, such as prairies, plains, large valleys, deltas and lowlands, which account for a majority of global food crop production. Results are consistent with the hypothesis that average farm yields plateau when they reach 75–85% of estimated national Yp, which appears to occur for rice in China and wheat in Germany. Prediction of when average crop yields will plateau in other countries is now possible based on the estimated Yp or Yw ceiling using this protocol.

1. Introduction

World population is projected to increase 35% by 2050, which will require a 70–100% rise in food production given projected trends in diets, consumption, and income (Bruinsma, 2009; Rosegrant et al., 2009; UNFPA, 2010). Increased food production can be achieved by raising crop yields on existing farm land, expanding crop production area, or both. Expansion of crop area, however, comes at the expense of substantial greenhouse gas emissions (IPCC, 2007; Searchinger et al., 2008), which would contribute to climate change (Karl and Trenberth, 2003).

The extent to which increased food production requires expansion of cultivated area will be determined largely by crop yield potential (Yp), which is defined as the maximum attainable yield per unit land area that can be achieved by a particular crop cultivar in an environment to which it is adapted when pests and diseases are effectively controlled and nutrients are non-limiting (Evans, 1993). In irrigated systems, Yp is determined by temperature regime and solar radiation during the growing season. Water-limited yield potential (hereafter called water-limited yield; Yw) is the relevant measure of maximum yield attainable in rainfed systems. Despite the importance of Yp and Yw to food production capacity, they are not explicitly considered in studies of indirect land use change as affected by policies about biofuels (Searchinger et al., 2008), conservation of biodiversity (Phalan et al., 2011), or future food security (Godfray et al., 2010). Accurate estimates of Yp and Yw are also needed to interpret yield trends in regions and countries where aggregate data indicate yield stagnation (Cassman et al., 2003; Lobell et al., 2009). For example, rice yields appear to have plateaued in Japan and China; maize yields have been stagnant in China, Italy, and France; and wheat yields are not increasing in northern Europe and India (Brisson et al., 2010; Cassman et al., 2010). Yield stagnation in these major grain production areas puts pressure on other regions to either accelerate yield growth rates or expand cultivated area to make up the difference between global supply and demand. Hence, understanding the cause of these yield

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plateaus is critical to determining whether it is possible to resume yield advance or if the focus should be placed on accelerating yields in other grain producing regions.

One explanation for yield plateaus is that average farm yields have approached a Yp or Yw ceiling. That is, plateaus occur because it is impossible for average yield in a region or nation to reach Yp or Yw for two reasons: (1) 100% of farmers cannot achieve the perfection of crop and soil management required to reach Yp or Yw, and (2) crop response to additional inputs exhibits a diminishing marginal yield benefit as yield approaches the ceiling, which decreases the marginal cost-benefit of additional inputs and reduces incentives to exploit the small remaining gap between farm yield levels and Yp or Yw. This is not to say that plateaus are due to reduced efficiencies in response to inputs. On the contrary, improved cultivars with improved resistance to biotic and abiotic stress resistance achieve higher yields than the older cultivars they replace at the same level of inputs, which means greater input use efficiencies. Instead, plateaus may reflect the fact that as yields rise toward the plateau, marginal return to additional inputs become smaller and thus farmers have less motivation to try and achieve highest possible yield. Therefore, average regional and national yields can be predicted to plateau when they reach 70–90% of Yp or Yw (Cassman, 1999; Cassman et al., 2003; Grassini et al., 2009). Because there is little evidence that the Yp ceiling has increased during the past 30 years in maize and rice (Cassman, 1999; Duvick and Cassman, 1999; Peng et al., 1999) or wheat (Graybosch and Peterson, 2010), accurate estimates of ceiling yield levels are critical to determine whether plateauing crop yields result from lack of an exploitable gap between average farm yields and Yp in irrigated systems, or Yw in rainfed systems.

At issue is whether available methods to estimate Yp and Yw are good enough to help interpret yield trends that indicate a plateau or to inform development of policies that seek to reduce GHG emissions from agriculture, including direct and indirect effects of land use change. Crop simulation models can be used to estimate Yp and Yw based on current management, genetic features of the crop, weather and water supply. But crop models that perform well in evaluation of yield at the field or farm levels do not generally perform well when scaled up to regional or national levels (Wit et al., 2005). In large part this performance problem reflects difficulty in scaling weather data from point estimates at ground-based stations to larger geospatial scales.

A common approach for estimating current or future crop yields at a global level utilizes a weather database interpolated to $0.5^\circ \times 0.5^\circ$ grid, or roughly 3100 km^2 at the equator (Fischer et al., 2002; Lobell and Field, 2007; Priya and Shibasaki, 2001). The strength of this interpolated grid approach is that it provides global coverage of terrestrial ecosystems. Two weaknesses of spatial interpolation of data are: (1) it reduces the degree of variability in temperature, rainfall, and solar radiation across a landscape due to variation in topography within the grid cell, and (2) the geospatial distribution of crop area within a grid is not uniform and is typically concentrated in certain zones across the landscape. The attenuation of variability in temperature, rainfall and solar radiation can result in over or under-estimation of yields for crops that rely on rainfall by as much as 10–50% (Baron et al., 2005). Furthermore, the quality of geospatially interpolated weather data is not uniform across the globe because geospatial density of weather stations is very low in some regions. Another approach is to assume highest yielding fields for a particular environment as yield potential yields, but these yields may be the result of a single good year and do not represent long-term average yield potential for a given location (Licker et al., 2010). Assuming all areas of the globe can be handled in the same way ignores complexity in the geospatial distribution of cultivated land due to differences in topography and weather. Use of actual weather data over a number of years from ground stations that are spatially congruent with geospatial distribution of crop production avoids such weaknesses associated with use of interpolated weather data or "averaged" crop production statistics in estimating Yp or Yw.

Another issue is the most appropriate time-step for weather data used to simulate crop yields. Previous global, national, and regional estimates of Yp or Yw are mostly based on weather data derived from monthly means or simulated climatic years based on historical variances (Andarzian et al., 2008; Deryng et al., 2011; Neumann et al., 2010; Nonhebel, 1994; Priya and Shibasaki, 2001; van Bussel et al., 2011). However, monthly means are too coarse and interpolating these means to derive daily values does not capture within month variability adding additional uncertainty to the weather input data. Accurate simulation of Yp or Yw requires a daily time step to fully capture the impact of current crop management practices, or adaptive management in response to changes in climate as well as the historical variability of weather within the course of the month. Both Yp and Yw are highly sensitive to the date of planting and cultivar selection in terms of maturity, which together determine the timing of key growth stages and length of crop-growing season (Cassman et al., 2010; Grassini et al., 2009; Wang and Connor, 1996; Yang et al., 2006). Such sensitivity is especially important to estimate Yp and Yw by simulation of crops grown in temperate agroecological zones, such as the U.S. Corn Belt, where length of growing season is determined by expected date of first and last frost. Specification of planting and maturity dates also are important in multiple cropping systems in tropical and semi-tropical regions where two or three crop cycles occur each year on the same field.

In addition to weather data with daily time-step, an appropriate simulation model is needed to estimate Yp and Yw. Models should be well documented and validated against yields of crops grown in fields where, apart from weather, yield-limiting factors have been eliminated (Kropff et al., 1993; Lobell et al., 2009; Yang et al., 2006). While some previous studies have used generic, non-species-specific relationships between incident solar radiation and plant biomass production to estimate net primary productivity (Penning de Vries et al., 1997; Doorenbos and Kassam, 1979), such models are not able to simulate crop phenology, which is controlled by species-specific traits essential for accurate simulation of crop maturity and grain yield.

Based on review of the literature, we conclude that available methods do not give robust, reproducible, and transparent estimates of crop Yp or Yw at regional to national scales. Given the need for accurate estimates of ceiling yield levels for interpreting current yield trends and for studies of future food security and land use under changing climate, we set out to develop an appropriate method for estimating these yield benchmarks at regional to national scales. To develop such a protocol requires addressing the following issues: (1) what are the minimum weather data requirements for accurate simulation of Yp or Yw at a given location, (2) what level of specificity in crop management practices is required, and (3) how best to scale up estimates of Yp and Yw from location-specific estimates to regional and national scales. These questions were examined for rainfed and irrigated maize in the USA (28 Mha and 4 Mha harvested area, respectively), irrigated rice in China (30 Mha), and rainfed wheat in Germany (3 Mha). Our attempts to answer to these questions led us to propose a protocol for estimating Yp and Yw at regional to national scales.

2. Materials and methods

2.1. Geospatial distribution of harvested crop area

A geospatial database of harvested crop area (Portmann et al., 2010) was used to identify regions with large crop production area.

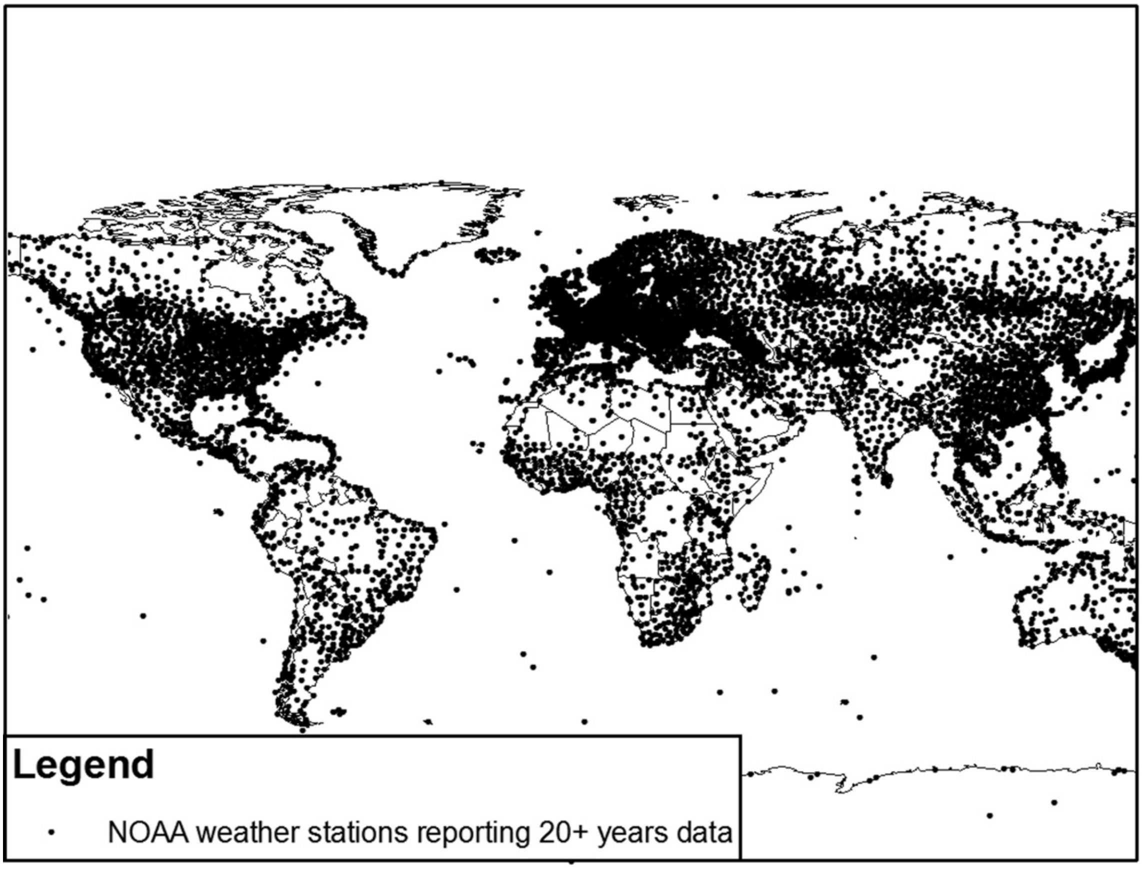

Fig. 1. Distribution of NOAA weather stations with 20+ years of weather data since 1985.

This dataset contains the harvested area of 26 crops on a $0.5^{\circ} \times 0.5^{\circ}$ global grid, and for each crop, it distinguishes irrigated from rainfed harvested crop area. To our knowledge, it is the most detailed and comprehensive geospatial database on crop area distribution currently available. Of particular note is that the geospatial distribution of crop area was based on nationally reported data corroborated by satellite imagery.

2.2. Selection of reference weather stations and quality control measures

Weather databases of sufficient geospatial coverage and quality are essential in simulating crop yields at larger scales. We used observed weather data from selected stations, referred to as reference weather stations (RWS), found in the National Oceanic and Atmospheric Association (NOAA), Global Summary of the Day (GSOD). This global dataset includes daily values for surface maximum and minimum temperature (*T*max, *T*min), precipitation, wind speed, and dew point temperature (National Oceanic and Atmospheric Association, 2010). Data from stations in this database undergo a number of quality control measures as described at: http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/. Geospatial coverage is quite dense in North America, Europe and East Asia, and reasonably well distributed in populated areas of south and southeast Asia, Africa, and Latin America (Fig. 1). Weather stations are sparse, however, in areas with low population density or lack of infrastructure.

Weather stations were only considered as a potential RWS if they: (1) had at least 20 years of data since 1980, (2) were located in a province or state that contained > 2% of total national production for the crop in question, and (3) had fewer than 10% of data-days and fewer than 30 consecutive data-days missing. Using the Portmann et al. (2010) geographic distribution of crop area, ArcGIS was used to iteratively sum the harvested area within a buffer zone of fixed radius around each station, and stations within a country were then ranked. The station with greatest harvested area within this buffer zone was selected as a reference weather station (RWS). All other stations near the selected RWS (within twice the distance of the buffer zone radius) were then eliminated from further consideration to avoid overlapping buffer zones, and the station with the largest harvested crop area among remaining stations was then selected as a second RWS. The process was repeated until >50% of nationally harvested area fell within 100 km of selected RWS. In some cases crop production area is highly concentrated such that >50% of nationally harvested area cannot be achieved without some overlap among RWS. In this case, 5 km incremental overlap was allowed until >50% of nationally harvested area could be achieved with 25 stations or less. This selection process avoided subjective selection of RWS, limited the number of stations required for estimation, minimized overlap of buffer zones used for weighting, and provided good geospatial coverage of regions that contributed most to total national production of the crop in question. Minimizing the number of RWS becomes important because information about crop management practices within buffer zones is also required for accurate Yp and Yw simulation, and it requires considerable effort to obtain these data (see Section 2.4 below). A buffer zone of 100 km was used for this study. Zones of 50 km and 150 km were also considered, but did not allow for 50% coverage of harvested area because of too much overlap (150 km) or not enough area covered (50 km) (data not shown). Preliminary evaluations of stability of Yp and Yw estimates based on number of consecutive years of weather data and amount of crop area covered by RWS buffers

Table 1
Influence of date of transplanting or direct seeding (D. seed) planting dates and maturity date, or both (day of year = DOY) on simulated Yp (Mg ha^{-1}) using NOAA-SR2 for select provinces and rice cropping systems.

Province	Season	Base Yp (Mg ha^{-1})	Transplant DOY		Maturity DOY		Transplant and maturity DOY	
			+7	−7	+7	−7	−7, +7	+7, −7
Sichuan	Single	9.2	−4%	3%	7%	−10%	10%	−13%
Anhui	Early	3.3	−11%	11%	15%	−15%	18%	−23%
Anhui	Middle	8.6	−5%	3%	13%	−14%	16%	−18%
Anhui	D.Seed	6.1	−15%	12%	−6%	−8%	22%	−24%
Anhui	Late	4.4	−10%	0%	4%	−10%	13%	−18%

indicated that 20 years and 40–50% area coverage was sufficient to obtain stable estimates. This was confirmed by more thorough analysis as provided in this paper.

Using this RWS selection procedure made it possible to obtain >50% coverage of total national harvested area for irrigated rice in China (∼29 Mha total harvested area, five-year average, 2004–2008) and irrigated maize in the USA (∼3 Mha total harvested area, 2004–2008) without need for overlap among RWS (Table 2). In contrast, rainfed maize production in the USA (∼28 Mha, 2004–2008) is highly concentrated in the central and eastern Corn Belt, as are weather station data, such that up to 25 km overlap was required between some of the RWS to cover 14 Mha (50%) of harvested area based on the Portmann et al. (2010) geospatial data. Because of relatively small land area and relatively large number of weather stations with good quality weather data in Germany, only 6 RWS were required to cover >50% of total harvested area of rainfed wheat (∼3 Mha).

Weather data for each selected RWS were subjected to quality control (QC) measures to fill in missing data and identify and correct erroneous values that occur due to technical problems common in weather data acquisition. A spatial regression test (SRT) (Hubbard et al., 2005) was used to check and correct weather data at a given RWS against data from nearby stations based on the strength of correlation between nearby and reference station data. Developed for use in the Midwest USA, this QC method was found to outperform other QC approaches in a wide variety of climate-zones (Hubbard et al., 2007; You et al., 2008). At least 2 nearest stations were used with the SRT to identify and correct missing and suspicious values for Tmin, Tmax, dew point temperature, wind speed, and precipitation. Typically about 0.5% of observations were corrected, roughly 2 days per year. Following Hubbard et al. (2005), a daily value was flagged as suspicious if it was greater than 3 standard deviations (5 for precipitation) from the SRT value, which is a regression-estimated value based on 15 days before and after the daily value in question. In rare cases where a single daily record was missing from the RWS and nearby stations (<0.01% of all values), the average of the preceding and succeeding day was substituted for the missing value.

Evapotranspiration, relative humidity, incident solar radiation, and vapor pressure are not measured or reported in the NOAA weather data, but they are required by one or more of the crop simulation models used in this study. Hence, evapotranspiration and relative humidity were estimated following Allen et al. (1998). Vapor pressure was estimated using the Wobus method (Gerald and Wheatley, 1984). Incident solar radiation was obtained in one of two ways: (1) derived from the square root of the difference between daily minimum and maximum temperature multiplied by extraterrestrial solar radiation and a constant (Hargreaves and Samani, 1982) or (2) obtained from NASA agroclimatology solar radiation data, which are available on a 1° by 1° global grid. These data were obtained from the NASA Langley Research Center POWER Project funded through the NASA Earth Science Directorate Applied Science Program. We therefore had two sources of NOAA weather data for crop simulation, both using actual data for temperature and rainfall but with different sources of data for solar radiation: either derived (Hargreaves and Samani, 1982), hereafter called NOAA-SR1, or based on solar radiation from the NASA-POWER database, hereafter called NOAA-SR2.

2.3. Soil properties

Soil texture and bulk density have a large influence on water holding capacity and are required for simulation of Yw (Saxton et al., 1986). For each RWS, the dominant agricultural soil within the 100 km buffer zone was identified. For U.S. maize production, soil texture was identified for the most abundant soil type associated with the densest maize production area within each RWS selected as a RWS for irrigated or rainfed production. This was achieved by evaluating soil types and area distribution in the SSURGO database (Soil Survey Staff, 2010) in relation to the geospatial distribution of 2009 maize area (NASS, 2010a) within each 100 km RWS buffer zone. When there were two or more soils of similar extent and congruence with maize area, the soil with highest land capability class (Klingebiel and Montgomery, 1961) was selected as the most representative soil for maize production in the RWS buffer zone. In Germany soils within each RWS were identified using a digital soil map (1:1.000.000) using soil profile descriptions for dominant soil types from Hartwich et al. (1995). For irrigated rice, soil water holding capacity is not a sensitive variable for simulation of Yp because it is assumed that farmers can apply irrigation whenever rainfall falls below crop water requirements. Therefore, simulations of rice Yp in China did not require specification of soil properties.

2.4. Crop management

For the crops and countries examined here, farmers have ready access to latest technologies and information regarding planting dates, seeding rates or transplanting patterns, and cultivars. Indeed,

Table 2
National estimated Yp and reported 5-year average (2004–2008) yields (taken from IRRI for China, FAO for Germany and NASS for the US).

Country-crop	Years	Water regime	Harvested area in 100 km buffer zones (Mha)	Harvested area[a] (Mha)	Coverage	Ya (Mgha^{-1})	Yp (Mgha^{-1})	Ya/Yp (%)
China-rice	86–08	IR	15.0	29.12	51%	6.4	7.8	82%
US-maize	86–08	RF	14.0	27.7	50%	9.7	13.2	73%
US-maize	86–08	IR	1.9	3.5	54%	11.7	15.1	77%
German-wheat	86–08	RF	1.6	3.1	52%	7.6	9.5	80%

[a] 2004–2008 average harvest area from FAO (2010) for China and Germany and NASS (2010b) for the US.

there are few barriers to alter management of these practices if such changes would result in higher yields and profit. For this reason, management specifications for all simulations were based on current average farmer practices in each location where Yp or Yw was simulated.

Management practices and the extent of harvested area for rice systems in China were obtained from agronomists in each of the major rice-producing provinces across China. Dominant rice cropping systems ranged from three, two, or one rice crop per year on the same piece of land depending on whether the climate was warm enough for year-round crop production. More than 40 different rice-based cropping systems were identified in 17 provinces. For each rice crop, in each of the different cropping systems, crop management data included plant population for direct-seeded rice or hill spacing in transplanted rice, date of sowing or transplanting and transplant seedling age, date of flowering and maturity, and the most widely used cultivar. Emergence was assumed to occur 7 days after direct seeding. Crop phenology (seeding, flowering, and maturity dates) and transplanting dates reported for each rice cropping system within a province were used to estimate genotype-specific coefficients required for simulation of Yp within RWS buffer zones located in that province using companion software of the rice simulation model (ORYZA2000).

Data for average U.S. maize sowing date by county were obtained from the USDA's Risk Management Agency (RMA), which requires farmers enrolled in USDA insurance programs to report their planting dates by field. For each county in which a RWS was located, the planting date was considered to be the date on which 50% of the maize area was planted (mean value for 2003–2008). Seeding rate and growing degree days required to reach maturity for the most common hybrids used were obtained from field researchers, seed company agronomists, and farmers familiar with crop management practices in buffer zone areas around each RWS. If long-term average yields simulated by the maize crop model (see Section 2.5 below) using the reported hybrid maturity (quantified by cumulative relative maturity days, called CRM) had a >20% risk of frost occurring before end of grain filling, CRM was adjusted a few days earlier until risk of frost was <20%. Hybrid maturity, quantified in cumulative relative maturity days (CRM), was adjusted down.

Phenological data for wheat in Germany (sowing, emergence, spike emergence, physiological maturity) were obtained from observations of the German Weather Service (DWD, www.dwd.de). Data of regional wheat area, yields, and the most widely used cultivars in different regions were obtained from the literature (Seling and Lindhauer, 2005; Seling et al., 2009), while information on most widely used seeding rate were obtained from wheat breeders and agronomists. Genotype-specific parameters for the cultivars used were obtained from the GENCALC program, which iteratively changes genotypic coefficients until simulation results match reported dates of phenological stages (Hunt et al., 1993).

2.5. Crop simulation

Crop Yp and Yw were simulated from 1990–2008 using ORYZA2000 for rice in China (Bouman et al., 2001), 1990–2008 using HybridMaize for maize in the US (Yang et al., 2004), and from 1983–1992 using CERES-Wheat for wheat in Germany (Ritchie et al., 1985). Each of these models requires daily values of maximum and minimum temperature and solar radiation to simulate Yp, and also rainfall for simulation of Yw. Grain yield outputs from the models are reported at standard moisture contents of 14, 15.5, and 13.5 kg H_2O kg^{-1} grain for rice, maize and wheat, respectively. Each of these models have been well documented and validated in field experiments with optimal management to allow expression of Yp or Yw across a wide range of environments (Boling et al., 2010; Bouman and van Laar, 2006; Feng et al., 2007; Ghaffari et al., 2001; Grassini et al., 2009; Liu et al., 2008; Singh et al., 2008; Timsina and Humphreys, 2006; Yang et al., 2006, 2004). ORYZA2000 requires four genotype-specific coefficients to determine phenological development and final maturity, and it simulates daily canopy CO_2 assimilation and total respiration. Daily net carbon assimilation is estimated by difference and assimilate is allocated to roots, stems, leaves and grain depending on stage of development (Bouman et al., 2001). HybridMaize is similar in structure to ORYZA2000, but only requires a single genotype-specific input parameter: growing degree days until the crop reaches physiological maturity (Yang et al., 2004). Most of the major seed companies provide information on growing degree days to physiological maturity for their commercial hybrids. Unlike ORYZA2000 and HybridMaize, which simulate gross photosynthesis and respiration separately, CERES-Wheat uses temperature-adjusted radiation use efficiency to convert photosynthetically active intercepted radiation into dry matter (Jones et al., 2003; Ritchie et al., 1985, 1988). CERES-Wheat requires 6 genotype-specific coefficients to simulate phenological development in response to temperature, photoperiod, and vernalization requirements.

2.6. Estimating Yp or Yw at regional and national scales

Regional or national estimated yield potential (Y_R^P) is a production weighted average defined as:

$$Y_R^P = \frac{\sum P_i^P}{\sum H_i} \text{ for all } i \text{ in the region and for } P_i^P = Y_i^P \times H_i \quad (1)$$

where P_i^P is the potential production, H_i is the harvested area within 100 km, and Y_i^P is the estimated Yp or Yw of RWS i. An estimate of Yp or Yw within a RWS 100 km buffer zone is derived from simulations based on the weather data from the RWS and crop management practices in the region as described above. For regions where more than one crop is grown each year on the same piece of land, such as the multiple rice cropping systems in China, Y_i^P is defined as total potential production of each cropping system (early-season, late-season, etc.) divided by the total area planted to all rice cropping systems simulated at that RWS. These national, long-term average Yp and Yw estimates were compared against reported 5-year average national yields (Ya). These Ya data are representative at the national scale, not at a regional scale. While this method of up-scaling works well for countries in which crops are grown in large, mostly homogenous topographies, as is the case for the crops and countries examined in this paper, modification of up-scaling will be required, such as use of smaller buffer zones and agro-climatic zones, in countries where crops are grown in regions with greater heterogeneity in topography.

2.7. Evaluation of requirements for robust Yp and Yw estimation

Simulations of Yw for rainfed U.S. maize and German wheat were evaluated using three sources of weather data: NOAA-SR1and NOAA-SR2 as previously described, and a benchmark data source that provides daily measurement of all parameters required for crop simulation. For maize, the benchmark databases were obtained from the High Plains Regional Climate Center (HPRCC, 2011), which is a network of weather stations in the western Corn Belt. For wheat, benchmark data were obtained from the German Weather Service (DWD, 2009). For irrigated rice in China, the benchmark weather data came from the China Meteorological Association (CMA, 2009). In each country, four sites were selected at which there were both a benchmark and NOAA weather station with at least 10 years of weather data (1990–2008 for US and China, 1983–1992 for Germany). Sites included Cedar Rapids, IA, Lincoln, NE, McCook, NE and Grand Island, NE in the USA, Bad

Hersfeld, Braunschweig, Düsseldorf, and Geisenheim in Germany, and Chengdu, Chongqing, Nanning, and Gushi in China.

To explore how many years of weather data are required to obtain a robust estimate of long-term average Yp or Yw, we simulated Yw at 23 sites across the U.S. Corn Belt from 1986–2009 and then calculated the average Yw for each and every consecutive interval of 2, 3, 4... and 23 years within these datasets. This gave us 21 observations of 2-year averages, 20 observations of 3-year averages, etc. at each site. The mean and standard deviation of all observations for each interval were then computed and used to calculate the coefficient of variation (CV).

To evaluate sensitivity of Yp and Yw to specification of management practices, simulations were performed using reported and modified management practices and crop phenology for selected sites. For selected simulations of rice Yp in China (in Houshan, Anhui and Chengdu, Sichuan), transplanting date (or seeding date for directly seeded systems), maturity date (representing an earlier or later maturing cultivar), and a combination of the two were adjusted by ±7 days compared to reported values. For selected rainfed US maize simulations (Grand Island, NE, Cedar Rapids, IA and Grissom, IN), planting date was adjusted by ±7 and ±14 days, cumulative relative maturity days were adjusted by ±4 days, seeding rate was adjusted by ±12,000 seeds ha^{-1} and a combination of these adjustments were compared with simulations made using the reported management. These sites were selected for this sensitivity analysis because they represent a wide range of rice cropping systems for irrigated rice in China, and for large differences in rainfall across the U.S. Corn Belt.

The influence of harvested area covered by RWS buffer zones contributing to national estimates of Yp or Yw was examined through calculations of Yw for US, Yp for China, and Yw for Germany by incrementally adding a station to the national estimate, following the previously described protocol for selecting stations, until 50% or more of nationally reported harvested area was covered by 100 km buffers. At issue was how much area coverage was needed to achieve a stable estimate of Yp or Yw.

3. Results

3.1. Evaluation of weather data requirements

For Yp or Yw simulated using benchmark weather data, NOAA temperature and rainfall coupled with derived solar radiation (NOAA-SR1) largely overestimated Yp and Yw compared to NOAA data with NASA observed solar radiation (NOAA-SR2) (Fig. 2). The overestimation was greatest for irrigated rice in China (+41%), moderate for rainfed wheat in Germany (+12%), and relatively small for U.S. rainfed maize (+4%). Within China, overestimation was greatest in Sichuan, a mountainous province where rice is grown in irrigated valleys as opposed to other provinces where topography is mostly flat. Topography in maize and wheat producing areas of the USA and Germany is also mostly flat. In the US Corn Belt, estimated solar radiation closely approximated observed solar radiation, perhaps because this area is similar to the one in which the estimation procedure was calibrated (Hargreaves, 1994).

Annual estimates of Yp or Yw were averaged from 1986–2009 (from 2 to 23-year averages) and the CV of these long-term, consecutive-year average estimates compared. Long-term average estimates were considered robust if they achieved a CV less than 0.05. For rainfed maize in the U.S. Corn Belt, the number of consecutive years of weather data required to obtain a Yw estimate with a CV of 0.05 was associated with mean annual rainfall across a transect of RWS in the U.S. Corn Belt (Fig. 3). At locations where annual rainfall was >900 mm (>−90° longitude), only 2–8 years consecutive weather data were needed whereas 11–15 years were required at sites with annual rainfall <700 mm (<−96° longitude). In a similar exercise for 10 RWS and 32 systems of irrigated rice in China, a CV of 0.05 was achieved within 12 consecutive years for all sites analyzed.

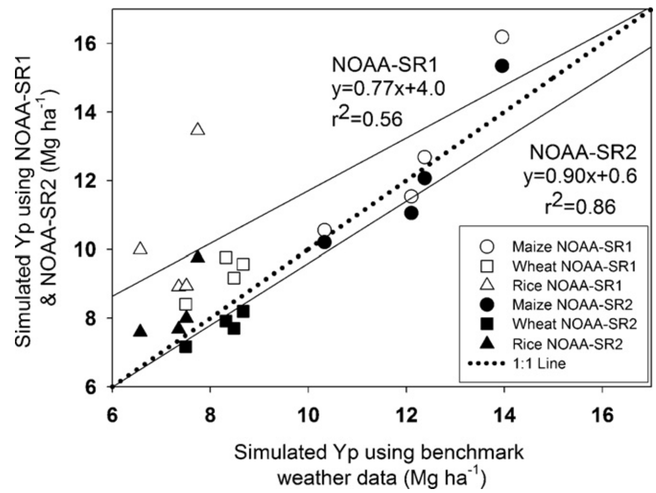

Fig. 2. Comparison of Yp simulated with two sources of NOAA weather data, either using derived solar radiation (NOAA_SR1) or observed solar radiation from the NASA-POWER database (NOAA-SR2) versus a benchmark from weather stations at which all required weather data were directly measured. Values shown represent 19-year means for each of four sites for rice and maize and 10-year means for each of four sites in Germany.

3.2. Sensitivity of Yp to changes in crop management

Relatively small changes in crop management specifications as input to yield simulations had relatively large effects on Yp of rice (Table 1). The impact of management was greatest in crop systems practiced in Anhui where farmers grow at least two crops annually on the same piece of land. For example, delay or advance of transplanting date by seven days resulted in Yp estimates that were −15 to +12% greater than reported transplanting dates. Similarly, increasing or decreasing crop maturity by seven days led to a range of −15 to +15% in simulated Yp. And if farmers combined both delayed or advanced transplanting with rice cultivars with a longer or shorter maturity, the range in simulated Yp varied by as

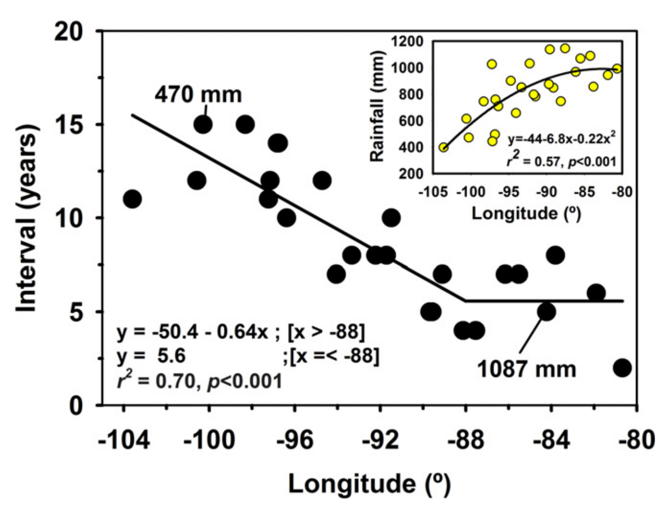

Fig. 3. Years of consecutive weather data required to obtain simulated Yw for maize in the U.S. Corn Belt with a CV of 0.05. The easternmost location is Youngstown, OH while the westernmost is Grand Island, NE. Average annual rainfall for two locations at extremes of the regression line are provided as reference points for the insert, which shows the east–west pattern of the annual rainfall gradient.

much as 46% (direct seeded; D.Seed) compared to current practices. In Sichuan with only one rice crop per year, Yp was somewhat less sensitive to effects of changes in management with a range of 25% in Yp due to combined effects of transplanting date and cultivar maturity. Like Sichuan, only one maize crop is planted each year in the U.S. Corn Belt. Changing relative maturity by ±4 days (roughly equivalent to 52 growing degree days, Celsius), resulted in more than 1 t ha^{-1} difference in Yw. And although the impact of increasing relative maturity by +4 days to achieve a longer growing season had a positive effect on simulated Yw, it increased the risk of frost occurrence before grain filling ends, which increased variability in Yw (data not shown).

3.3. *Geospatial coverage necessary for accurate characterization of national Yp and Yw*

National estimates of Yw for both U.S. maize and wheat in Germany were robust with only a small portion of national production area coverage. For example, average simulated Yw of U.S. rainfed maize ranged from 13.4 to 14.3 t ha^{-1} as the proportion of total rainfed maize area covered by RWS buffer zones increased from about 10% to 40%. In contrast, estimated national Yp of irrigated rice in China varied from 12 t ha^{-1} to about 8.0 t ha^{-1} as the proportion of covered area increased from 5% to 40% of total rice area (Fig. 4). This is due to three factors: (i) selection protocol for choosing RWS, (ii) spatial distribution of rice yields in China, and (iii) wide diversity of rice cropping systems found in China, where 2 or even 3 rice crops are planted each season, making windows for optimal sowing and harvesting relatively narrow. According to the protocol, the first RWS selected are those in areas with greatest rice production area density within the 100 km buffer zones around candidate weather stations. In China, these areas also have the highest yield potential, meaning that as lower-yielding production areas are added to the weighted national average, the estimated national Yp declines. It therefore required at least 40% coverage of harvested crop area to attain consistent national yield estimates for irrigated rice in China due to the large diversity of cropping systems. In contrast, stable estimates of Yp or Yw were obtained with relatively low coverage of harvested crop area for US maize and wheat in Germany where topography, climate, and cropping systems are relatively homogeneous. In all three countries, coverage of 40% of harvested area within 100 km of RWS provided robust estimates of Yp or Yw and estimates were not improved by adding additional RWS to increase coverage of harvested area.

3.4. *National Yp and Yw estimates*

National Yp estimates for irrigated rice in China and maize in the USA, and rainfed Yw for U.S maize and rainfed wheat in Germany are given in Table 2. Each estimate is based on selected RWS that include at least 50% of total production area for each crop, which required 22 RWS and nearly 100 simulations for Yp of rice in China (including the different rice cropping systems), 24 RWS and an equivalent number of simulations for Yw of US rainfed maize, 4 RWS and simulations for Yp of U.S. irrigated maize, and 6 RWS and simulations for Yw of rainfed wheat in Germany. In China, multiple cropping systems and the location of some RWS buffer zones across neighboring provinces required a large number of simulations based on the rice cropping systems in each province.

Average farm yields of rice in China and wheat in Germany were 82 and 80% of estimated national Yp and Yw, respectively. In contrast, current average Yw of rainfed U.S maize was only 73% of estimated Yw, which indicates a larger exploitable yield gap than for rice in China or wheat in Germany. Likewise, rainfed US maize has a larger yield gap than irrigated maize.

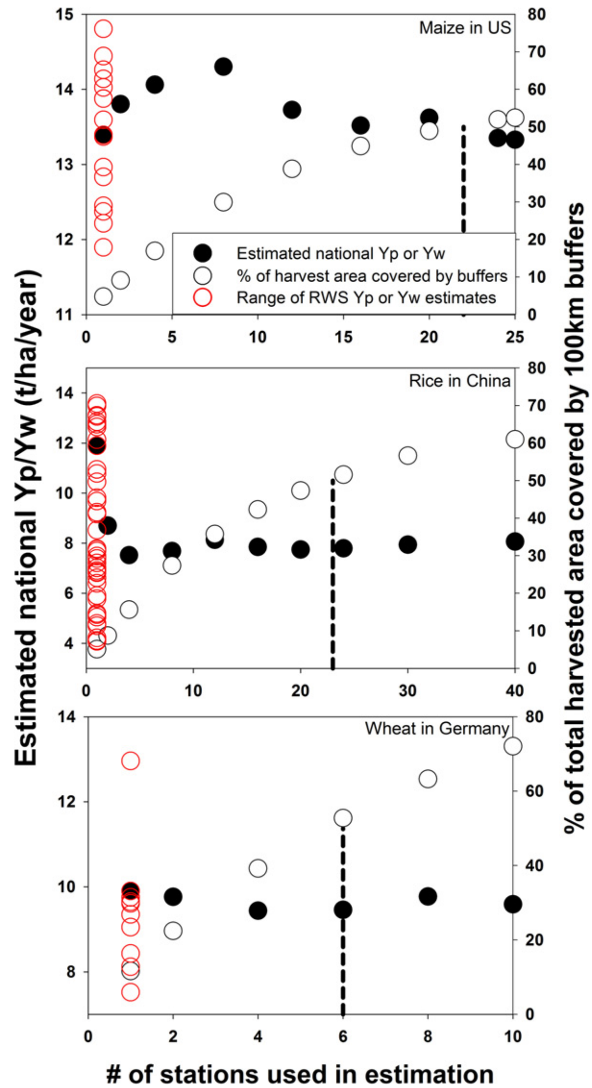

Fig. 4. Variation in estimated national Yp or Yw maize in the US, rice in China and wheat in Germany as influenced by the number of reference weather stations (solid black circles) and associated proportion of harvested total crop area used to simulate Yp or Yw (open black circles). Range of simulated Yp or Yw at all reference weather stations (RWS) are shown by the open red circles. The number of RWS at which 50% coverage of national harvested area occurs is shown by the black dotted line.

4. Discussion

Quantitative analyses of food security and environmental change are often performed to help guide formulation of regional and national policies. Accuracy, reproducibility, and transparency are essential attributes of such studies in order to allow challenge by others and to instill confidence in the results. These attributes are difficult to achieve in estimations of Yp and Yw due to limitations on quality of weather data at appropriate geospatial densities that are congruent with distribution of harvested crop area, scarcity of geospatially explicit information on crop management practices and soils, and lack of appropriate crop models. Results from the current study, however, indicate it is possible to attain robust and transparent estimates of national Yp or Yw if careful attention is given to the more sensitive components of Yp and Yw estimation. The methodology explored within this paper is most suitable for countries in which crops are mostly grown in prairies, plains, large valleys, deltas, and lowlands where topography is relatively homogenous. It is noteworthy that a large majority of global food crop production of the major cereal crops occurs in countries where these crops are grown on prairies, plains, large valleys, deltas, and lowlands. Moreover, the approach used here would be applicable to countries in which crops are grown in more complex topographies although protocols may require modification. For example, buffer zones of 50 km, 100 km and 150 km were considered in the current study (data not shown). While 50 km zones were unable to capture more than 40% of harvested area without a large number of RWS, especially in the US and China, 150 km zones caused too much overlap among candidate weather stations. For these reasons the 100 km buffer zones were chosen for this analysis. In countries where crops are grown in more heterogeneous landscapes than those examined in this paper, smaller buffer zones may prove more appropriate and it may be necessary to up-scale estimates of Yp or Yw from RWS to national levels using extrapolation based on agro-climatic zones. In addition to smaller buffer zones, beneficial future work would also examine variability in soil water holding capacity and its effect on simulation and upscaling results. For the two countries where Yw was simulated, terrain is relatively flat and soil types on which the majority of the crop is grown are relatively uniform and so only a single, dominant soil type was used as input into model simulations.

Estimates of Yp and Yw are significantly affected by several key factors. These include weather data quality and estimation procedures, specification of planting date and cultivar or hybrid maturity, the number of years simulated to estimate long-term average Yp or Yw, and geospatial weighting procedures to arrive at aggregated estimates at provincial or national scales. Each of these factors affect estimates of Yp or Yw to a greater or lesser degree depending on the specific cropping systems, location, and distribution of available data for the crop and country under investigation. For example in U.S. rainfed maize, variability in estimates of Yw depended on rainfall with high rainfall areas (>850 mm $year^{-1}$) requiring only 5–7 years of weather data to achieve a CV < 0.05 while more than 10 years were required to achieve a similar low CV for estimates of Yw in low rainfall areas (<700 mm $year^{-1}$). Thus it seems likely that duration of weather data required for robust simulation of long-term Yw increases as rainfall decreases or rainfall variability increases. For irrigated rice in China, however, no clear trend with rainfall was observed because irrigation eliminates yield-reducing impact of dry years.

The source of solar radiation data was also a sensitive factor in simulation of Yp or Yw. For irrigated rice in China, estimates of solar radiation performed poorly in simulating Yp in regions where topography was mountainous. Although the weather stations themselves are located on flat terrain, temperature in these areas may be more affected by mountainous climate (thinner air, rain shadow affects, and trapped air) rather than by cloud cover and solar radiation, which makes derivations of solar radiation based on diurnal temperature range a poor proxy for incident radiation (Thornton and Running, 1999; Winslow et al., 2001). The overestimation in non-mountainous regions may result from particulate air pollution, which reduces incident solar radiation and increases night time temperature and is subsequently high in the industrialized central and eastern China where a majority of rice is grown (Menon et al., 2002). In contrast, estimation of solar radiation based on the difference in *Tmin* and *Tmax* appears to be much more accurate for simulation of crop Yp and Yw in the Midwest USA because the algorithm for the derivation was based on research conducted in this region (Hargreaves, 1994), and because there is relatively little air pollution. But given the lack of accuracy in modeled solar radiation in areas with variable topography or with particulate air pollution, a standard method for estimating Yp or Yw would preferably rely on observed or satellite derived solar radiation (Bai et al., 2010; White et al., 2011).

Results from this study emphasize the importance of specifying current crop management practices to obtain relevant estimates of Yp or Yw at regional or national scales. While some may argue the value of simulating maximum possible Yp or Yw without regard to current management practices and cropping systems, such estimates do not account for the biophysical and socio-economic constraints under which farmers must operate. Indeed, historically and globally farmers are efficient in allocating their land, labor and capital to optimize profit and reduce risk (Herdt and Mandac, 1981; Hopper, 1965; Sheriff, 2005). For the three countries in which yield gap was evaluated in the current study, crop yields are relatively high and farmers have access to recommendations about best management practices. There are typically no barriers to farmer adoption of earlier or later sowing, use of longer or shorter maturity cultivars, different seeding rates or transplanting patterns if farmers believed that such changes made a significant difference in yield and profit. And in multiple cropping systems farmers are not seeking to optimize production of a single crop but rather of an entire system that includes several crops, such as the case of irrigated rice systems in much of China. Therefore, farmers are likely to use the most appropriate combination of sowing date and crop maturity for their cropping system considering risks and costs associated with other options. And while there might be small yield gains from changing plant populations from current practices, there is no published evidence defining "optimal" populations across the wide range of environments evaluated in this study.

The impact of using appropriate specification of crop management can be seen in both local and regional or national scales. For example, a change of only 7 days in planting date for irrigated rice in China affected simulated Yp by as much as a 1 Mg ha^{-1} or more. Given the harvested area of irrigated rice in Anhui Province, a difference of 1 Mg ha^{-1} represents 2.7 million metric tons total production, which is equivalent to 550,000 ha of high quality farm land at current average yield levels or the annual rice consumption of over 25 million people at current rice consumption levels in China (Zhai and Yang, 2006). Given this sensitivity to sowing date, estimates of Yp or Yw based on mean monthly weather data, or weather data derived from monthly means, can lead to large bias toward over- or under estimation depending on the difference between actual average sowing date and the assumed (or inferred) sowing date at the beginning, mid-month or end of the month, to accommodate use of monthly mean weather data.

Temperature and cumulative intercepted solar radiation during the growing season have a large influence on Yp. Total intercepted radiation is sensitive to both intensity of solar radiation (MJ m^{-2} d^{-1}) and length of growing season. Length of growing season is governed by temperature regime and crop management with regard to planting date and maturity of the most widely used crop cultivars. Density of plants per unit land area also influences amount of intercepted solar radiation. Therefore, estimation of Yp and Yw relevant to dominant cropping systems in a region requires specification of planting date, crop cultivar maturity, and plant density typically used by farmers in that region.

Because of the detailed information required to accurately simulate crop yield in each region, it is expedient to limit the number of RWS required for robust and reproducible estimates of Yp or Yw at a national scale. At the same time, if adequate area is not represented, Yp or Yw estimates may not provide accurate representation at a national scale. This is especially true in more complex cropping systems such as for rice in China where the initial RWS selected in China was from a province where only a single, high-yielding rice crop was grown, which is not typical of the majority of rice production in that country. Subsequent stations were located in provinces that produce more than one crop per year and for which the Yp of each of these multiple crops is much lower. The national Yp estimate for China, as well as every other crop and country analyzed, varied little after 40–50% of harvested area was within the buffer zones of selected RWS. While size of buffer zones may need to vary depending on size of country for which national Yp or Yw estimates are desired, achieving 50% coverage of harvested area is likely to provide robust estimates of crop production potential based on results from the current study, which included contrasting crops with a wide range of water regimes and cropping system complexity.

Average farm yields of rice in China and wheat in Germany were 82 and 80% of estimated national Yp and Yw, respectively. In contrast, current average Yw of rainfed U.S maize was only 73% of estimated Yw, which indicates a larger exploitable yield gap than for rice in China or wheat in Germany. Both China and Germany have seen very little or no growth in yields of rice and wheat, respectively, for the past decade, especially compared to previous decades (FAO, 2010), despite continued progress in agricultural technology and a trend toward higher prices. Similarly, yield of irrigated U.S. maize has not increased in the past decade and in this study current average yields are estimated to be 77% of Yp. These estimates of yield gap for rice in China, wheat in Germany, and irrigated maize in the USA are consistent with the hypothesis that average national yields begin to plateau when average farm yields reach 75 to 85% of Yp or Yw (Cassman et al., 2003; Lobell et al., 2009). This yield level has been proposed as the practical limit for national average farm yields because it is neither logistically feasible nor profitable for 100% of farmers to achieve yields equivalent to maximum biophysical potential yields. Therefore, analysis of future global food security should restrict crop production potential to some fraction of Yp and Yw to avoid over estimating national and global food production potential.

5. Conclusions

Results from this study suggest improved protocols to obtain robust, transparent, and reproducible estimates of Yp and Yw at local, regional, and national scales for countries in which crops are produced in areas with relatively homogeneous topographies. Such a protocol would have the following components:

(1) use real weather data with daily time step and avoid monthly means, or data derived from monthly means, and derived solar radiation;
(2) 15 years of weather data for rainfed agriculture, while 5 years may be sufficient for estimates of Yp for fully irrigated production systems;
(3) 50% coverage of harvested area using a procedure to select regions with greatest crop production density;
(4) specification of current average sowing date, cultivar or hybrid maturity, and plant population that gives maximum yield with this sowing date and cultivar/hybrid maturity. Without well documented evidence of what this optimal plant population is, estimates of Yp and Yw should be based on current average plant population used by farmers in the target location and cropping system;
(5) an appropriate weighting procedure to estimate Yp or Yw at regional or national levels from point estimates at selected reference weather stations (such as up-scaling based on harvested area within buffer zones around simulation sites); and
(6) an appropriate crop model that has been validated against field data in which crops have been grown to produce yields that approach Yp and Yw.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2012.11.018.

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