

## CLIMATE CHANGE AND AGRICULTURE RESEARCH PAPER

# The soybean yield gap in Brazil – magnitude, causes and possible solutions for sustainable production

P. C. SENTELHAS<sup>1\*</sup>, R. BATTISTI<sup>1</sup>, G. M. S. CÂMARA<sup>2</sup>, J. R. B. FARIAS<sup>3</sup>, A. C. HAMPF<sup>4</sup>  
AND C. NENDEL<sup>4</sup>

<sup>1</sup> *Department of Biosystems Engineering, ESALQ, University of São Paulo, Piracicaba, SP, Brazil*

<sup>2</sup> *Department of Plant Production, ESALQ, University of São Paulo, Piracicaba, SP, Brazil*

<sup>3</sup> *National Soybean Research Center, EMBRAPA, Londrina, PR, Brazil*

<sup>4</sup> *Leibniz Centre for Agricultural Landscape Research, ZALF, Müncheberg, Germany*

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## SUMMARY

Brazil is one of the most important soybean producers in the world. Soybean is a very important crop for the country as it is used for several purposes, from food to biodiesel production. The levels of soybean yield in the different growing regions of the country vary substantially, which results in yield gaps of considerable magnitude. The present study aimed to investigate the soybean yield gaps in Brazil, their magnitude and causes, as well as possible solutions for a more sustainable production. The concepts of yield gaps were reviewed and their values for the soybean crop determined in 15 locations across Brazil. Yield gaps were determined using potential and attainable yields, estimated by a crop simulation model for the main maturity groups of each region, as well as the average actual farmers' yield, obtained from national surveys provided by the Brazilian Government for a period of 32 years (1980–2011). The results showed that the main part of the yield gap was caused by water deficit, followed by sub-optimal crop management. The highest yield gaps caused by water deficit were observed mainly in the south of Brazil, with gaps higher than 1600 kg/ha, whereas the lowest were observed in Tapurah, Jataí, Santana do Araguaia and Uberaba, between 500 and 1050 kg/ha. The yield gaps caused by crop management were mainly concentrated in South-central Brazil. In the soybean locations in the mid-west, north and north-east regions, the yield gap caused by crop management was <500 kg/ha. When evaluating the integrated effects of water deficit and crop management on soybean yield gaps, special attention should be given to Southern Brazil, which has total yield gaps >2000 kg/ha. For reducing the present soybean yield gaps observed in Brazil, several solutions should be adopted by growers, which can be summarized as irrigation, crop rotation and precision agriculture. Improved dissemination of agricultural knowledge and the use of crop simulation models as a tool for improving crop management could further contribute to reduce the Brazilian soybean yield gap.

## INTRODUCTION

The improvement of agricultural production around the world is a challenge that must be overcome by increasing crop yield, in order to guarantee food and energy supply. In this context, the soybean crop plays an important role since it is a source of food and energy and one of the major global commodities. Brazil, the USA and Argentina are the main producers. In these countries, soybean yield is affected by several abiotic and biotic factors leading to yield gaps. In the

present study, the objectives were to present an overview of the yield gap concept and to determine the magnitude of soybean yield and yield gaps in the main producing regions in Brazil, their main causes and possible solutions to reduce these gaps and improve yields.

Food and energy security: land expansion and yield increase

Food, fibres and energy demand are increasing due to a growing population, which make agriculture a strategic activity in many countries around the world. The

\* To whom all correspondence should be addressed.  
Email: [pcsentel.esalq@usp.br](mailto:pcsentel.esalq@usp.br)

main challenge for agriculture in the near future is to produce more with less rural labour force, since 0.67 of population is going to live in cities in 2050 v. 0.46 in 2014, a value estimated by the FAO (2014). The other challenges for food, fibre and energy production are the efficient use of inputs and sustainable methods to adapt crops to climate change in order to maintain or increase yields (FAO 2009).

The future world food demand faces three major challenges: the world population will continue to rise: 9.55 billion people are estimated for 2050 (FAO 2014). The increase in the per capita income will lead to changes in people's diets, from 2860 kcal in 2015 to 3070 kcal in 2050 (Alexandratos & Bruinsma 2012) – mainly towards more meat consumption – which further increases the pressure on land availability. Finally, continued competition exists for land allocated to bioenergy or food crops. Regardless, food production needs to increase by 70% until 2050. For this, it is necessary to create local policies, markets and food chains to improve food production at a regional level, reducing international trade and enabling bioenergy generation with the exceeding production in locations with high yields (FAO 2009). Bioenergy should be carefully considered in this context, since the IPPC (2013) classify bioenergy as having potential negative consequences for food production and supply.

In developing countries, land is still available for agricultural expansion, with appropriate soil and climate. Here, the challenges are associated with the dissemination of agro-technology and adapted management for obtaining higher yields. Among the developing regions around the world, Latin America is the one with the highest potential for agricultural land expansion (54%) in order to achieve the food, fibre and energy demand projected to 2050 (FAO 2014). However, land expansion for agricultural use often conflicts with contrary land use targets, such as conservation of natural resources, unique ecosystems, biodiversity and other ecosystem services. For this reason, these developing regions, which usually have a population increase higher than developed countries, will need to increase their crop yield in terms of marketable crop production per unit of area and time (Cassman 1999).

Increasing crop yield will remain a critical and essential component for a global strategy to secure food and energy supply while also protecting natural resources and environmental quality for future

generations (Lobell *et al.* 2009). Brazil has a total area of 850 million hectares (ha). The legal Amazon Rainforest reserve and other natural biomes represent 503 million ha, while pastures and crops cover 211 and 71 million ha, respectively. Available land for agricultural expansion is estimated as c., 65 million ha (IBGE 2009), targeting expansion of agriculture mainly to degraded pasture and marginal lands.

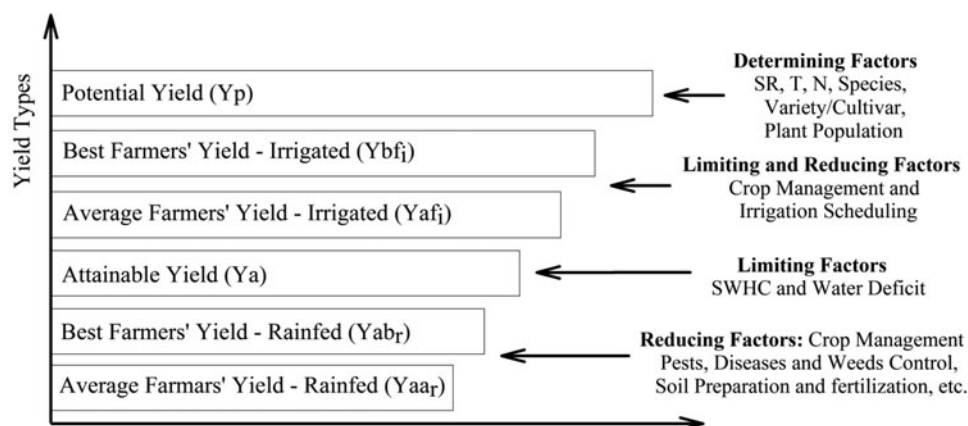
Soybean is one of the main crops in Brazil, having huge social and economic importance. It is used as food, animal feed and to produce biodiesel and it is considered highly relevant to analyse its yield patterns in order to identify the magnitude and causes of yield gaps, and to look for possible technological solutions in the short, medium and long term.

### Yield types and their conditioning factors

The relationship between different yield levels determines the yield gaps and their determining factors. Specific yield levels are used by different authors. Lobell *et al.* (2009) used the highest yield as the definition of potential yield, followed by experimental yields, maximum farmer's yields and average farmer's yields (Yaar). Bhatia *et al.* (2008) and Battisti *et al.* (2012) classified yield levels as potential, attainable and actual, as also used by van Ittersum *et al.* (2013), who used the term exploitable yield instead of attainable yield, showing that the difference between exploitable and actual yields is the maximum that the farmer can gain under rainfed conditions through better crop management. Liang *et al.* (2011) used potential yield ( $Y_p$ ) and the maximum and minimum yields from field experiments for evaluating the importance of technology on crop systems. Hall *et al.* (2013) evaluated the yield gap by comparing  $Y_p$  with yields from trial experiments, commercial field and reporting surveys at a county level.

Six different conceptual types of yields can be considered, based on previously cited work. The highest yield is the potential which has a theoretical characteristic, since it is difficult to reach in the field. Potential yield can be determined in different ways, but in general is assumed as yield obtained without growth limitations such as water, nutrients, pests, or diseases (Fig. 1), being influenced only by the interaction between the genotype and environmental factors, such as solar radiation, temperature and photoperiod (van Ittersum & Rabbinge 1997).

The  $Y_p$  is determined or estimated by crop models or field experiments with all crop management



**Fig. 1.** Types of yield and respective production factors. Adapted from Rabbinge (1993); van Ittersum & Rabbinge (1997); Lobell *et al.* (2009); Hall *et al.* (2013); van Ittersum *et al.* (2013).

factors under control and without water stress. When crop models are used, perfect management is assumed, without any limiting factors, while in field experiments it is necessary to have complete control of the environment in order for  $Y_p$  not to be underestimated (Lobell *et al.* 2009; van Ittersum *et al.* 2013; Hoang 2013).

Following  $Y_p$ , the next yield level is that cultivated under irrigation, including the best farmer's ( $Y_{bfi}$ ) and average farmer's ( $Y_{afi}$ ) yields, where the limiting (water stress) and reducing (crop management) factors are considered together with the determining factors. The differences between them are caused by crop management and irrigation scheduling (Fig. 1). The different levels of irrigation technology and crop management are important factors separating farmers in the two groups, the best with higher levels of technology ( $Y_{bfi}$ ) and the average with medium levels ( $Y_{afi}$ ). According to Hoang (2013), factors such as type of labour and region of production are responsible for crop efficiency and farm infrastructure affecting the yield level.

The third yield level is attainable yield ( $Y_a$ ), which is limited only by water availability in the soil; it can also be called water-limited yield (Lobell *et al.* 2009). It is the  $Y_p$  penalized by the water deficit, and thus influenced by soil water holding capacity, rainfall, evapotranspiration, surface slope and crop sensitivity to water deficit (Gilbert *et al.* 2011; Battisti & Sentelhas 2015). Attainable yield is a theoretical value since it also depends on crop management. van Ittersum *et al.* (2013) consider a lower yield level limited by water and nutrient availability, whereas crop models only consider nitrogen nutrition to penalize crop yield.

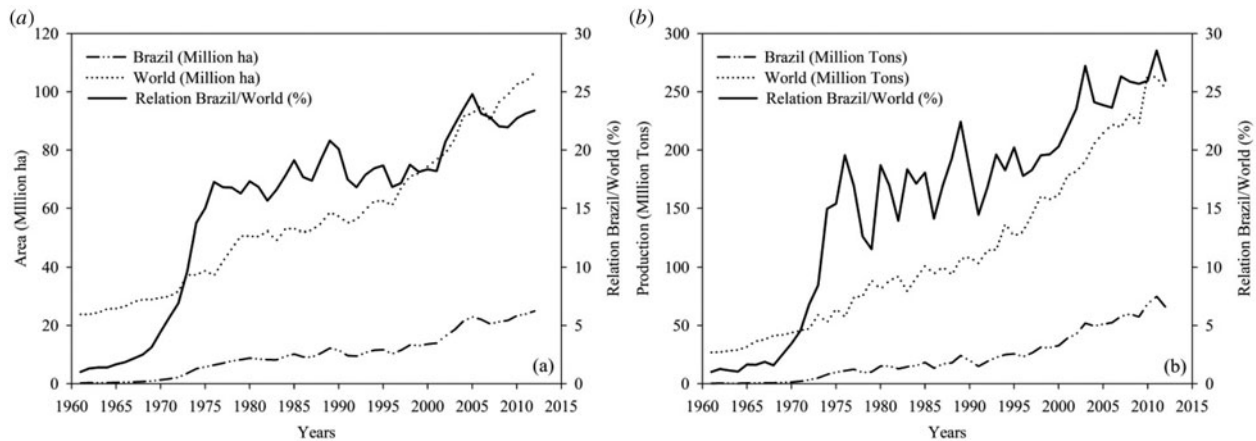
Below  $Y_a$ , two further levels consider different factors of crop management: best farmer's yield ( $Y_{abr}$ ) and average farmer's yield ( $Y_{aar}$ ) for rainfed conditions. These yields are obtained when  $Y_a$  is penalized by reducing factors associated with crop management, such as pest, disease and weed control, and soil preparation and fertilization. In conclusion, the final yield obtained in the field will be the result of the interaction of determining, limiting and reducing factors.

The  $Y_p$  and  $Y_a$  can be obtained from crop simulation models or from field experiments with optimum management. At this point, it is important to be aware that in field experiments,  $Y_p$  only can be achieved once limiting factors are controlled. Considering that, Hochman *et al.* (2012) and van Ittersum *et al.* (2013) recommend the use of a relative level, near to 80% of  $Y_p$  or  $Y_a$ , to represent what happens under irrigated or rainfed conditions, respectively.

#### Yield gap – definition, concepts and importance

The yield gap is the difference between different yield types for a specific condition considering spatial and temporal scales. It is important to look for what the researchers want to identify when considering the yield gap. In general, the yield gap is a value expressed by the difference between potential and the average farmers' yields. So, in this case it is defined as the total yield gap, which includes all determining, limiting and reducing factors.

Figure 1 presents different types and levels of yield gap and the factors that affect them. For example, the difference between  $Y_p$  and  $Y_{afi}$  shows that the



**Fig. 2.** Soybean area (a) and production (b) in Brazil and their relation with world area and production from 1961 to 2012. Source: FAO (2013).

yield gap is due to sub-optimal crop management and irrigation scheduling. Rodrigues *et al.* (2013a) showed that irrigation management, water distribution uniformity, soil salinity, crop variety, soil-water conservation and fertility, pests and diseases can affect soybean yield. In particular, soybean Asian rust pressure is increased when the crop is irrigated.

In rainfed crops, the yield gap can be obtained by the difference between  $Y_a$  and  $Y_{a,r}$ , since in this condition the maximum possible yield is  $Y_a$  (van Ittersum *et al.* 2013). While the difference between  $Y_p$  and  $Y_a$  defines the yield losses caused by water deficit, the difference between  $Y_a$  and  $Y_{a,r}$  shows how much of the losses are due to crop management. According to van Ittersum *et al.* (2013), such an approach will depend on the type of  $Y_a$  considered, i.e. limited only by water deficit or by water and nutrient restrictions.

The proposal to split farmer's yield into two types, with best and average levels of technology, defines a framework in which the farmers that employ a low standard of technology can compare their own performance with those that use higher levels of technology. This learning process can be enhanced by analysis of the best and average farmers' yields, identifying the main differences in crop management between them. After that, actions to improve crop performance in the fields can be defined according to the investments required. In this kind of analysis, market, policies, infrastructure and institutional factors should also be evaluated to define the feasibility of the investments (van Ittersum *et al.* 2013).

Lobell *et al.* (2009) described two main reasons for understanding yield gaps: firstly, it helps to inform projections of future yields for different regions and crops

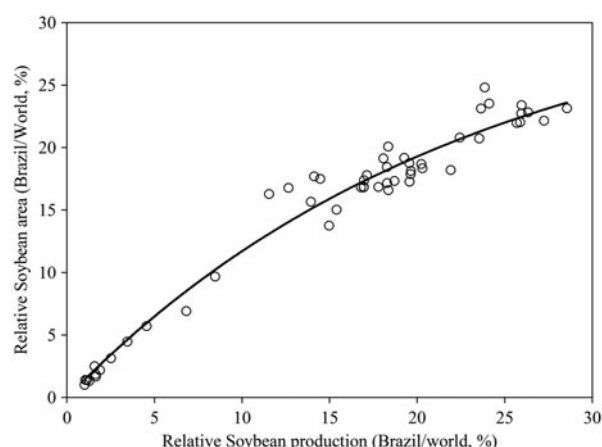
because close proximity of yields to their upper limits may indicate that growth rates are likely to slow in the future; and secondly, knowledge of factors that contribute to the yield gaps is useful for efficiently targeting efforts to increase yield and production. The focus is on reducing the yield gap in regions with greater potential than others to support higher yields in a sustainable manner, where potentials are associated with favourable climate, soil and access to technologies, such as irrigation (van Ittersum *et al.* 2013).

#### Soybean production in Brazil

Brazil is one of the most important soybean producers in the world, representing >0.25 of the soybean market in 2011, with <0.25 of soybean cropping area in the world (Fig. 2). The total area cultivated in the world increased from 24 million ha in 1960 to 106 million ha in 2012, while in Brazil this increase was from 0.24 to 25 million ha. Such increase of the soybean area in Brazil was due to suitable growing conditions in the country for soybean production and for the expansion of the crop to the north (low latitudes), with the selection of cultivars less sensitive to photoperiod and with long juvenile periods (Destro *et al.* 2001). The prolonged juvenile periods are important for low latitudes, allowing the crop to extend the vegetative phases, giving it more time to fix carbon and accumulate nitrogen, increasing  $Y_p$  (Sinclair *et al.* 2005).

One of the ways to evaluate the Brazilian performance for soybean production is by correlating the Brazil/world relative production and relative area (Fig. 3). Brazil has seen an increase in both production and area since 1961, however with yield increasing





**Fig. 3.** Relationships between Brazil/world relative soybean area and relative soybean production. Source: FAO (2013).

more than the production area. This trend is clear evidence that the yield gap reduction possibly occurred due to improvements in soil fertility, mechanization, better commodities prices, investment in research and development of new technologies, crop breeding and adoption of public policies such as agro-climatic risk zoning.

In Brazil, soybean is produced from the south to north, in 14 states (Table 1). The average yields from 1990 to 2011 varied considerably. The Mato Grosso state had the highest yield, with 2778 kg/ha, followed by Rondônia, Paraná, Distrito Federal and Goiás, with yields above the national average (2400 kg/ha). The lowest yield was in Rio Grande do Sul state, with 1880 kg/ha, which is associated with frequent droughts during neutral and negative El Niño Southern Oscillation (ENOS) events (Alberto *et al.* 2006), when less rainfall is received in Southern Brazil (Berlato *et al.* 2005).

Total Brazilian soybean production was 82.2 million tonnes in 2013, with Mato Grosso, Paraná, Goiás, Mato Grosso do Sul and Rio Grande do Sul being responsible for c., 0.81 of it. It is important to highlight that land expansion for soybean production is limited in southern states (Rio Grande do Sul and Paraná), whereas in other states such as Mato Grosso it is still occurring and yield has increased substantially.

## MATERIALS AND METHODS

A simple crop model was calibrated using crop yield and phenology data obtained from 17 different counties in the states of Rio Grande do Sul, Santa Catarina,

Paraná, São Paulo and Mato Grosso do Sul, Brazil. Field experiments for soybean cultivar competition were developed by the Pro-Seeds Foundation between the crop seasons of 2008/09 and 2010/11, with 101 Brazilian soybean cultivars sown between 27 October and 24 December.

The FAO crop yield model Agroecological Zone (Kassam 1977) was used to estimate  $Y_p$ , while the water deficit yield depletion model (Doorenbos & Kassam 1979; Rao *et al.* 1988) was used to estimate  $Y_a$ . The  $Y_p$  was estimated considering only the interaction between the genotype and solar radiation, photoperiod and temperature, according to the following equation:

$$Y_p = \sum_{i=1}^m 1GP \times C_{LAI} \times C_{RESP} \times C_H \times (1 - C_W)^{-1} \quad (1)$$

where  $Y_p$  is in kg/ha;  $GP$  is gross photosynthesis (kg DM/ha day);  $C_{LAI}$  is the depletion coefficient to leaf area index (LAI);  $C_{RESP}$  is the depletion coefficient associated to the maintenance respiration process (function of the air temperature);  $C_H$  is crop harvest index;  $C_W$  is the water content in the harvested part of the plant;  $i$  is the day in the crop cycle; and  $m$  is the number of days of the crop cycle from sowing to harvesting, which was adjusted for each region (R. Battisti, personal communication). The crop cycle was adjusted for the main maturity groups of each region, ranging from early (Groups 6–7) in the southern locations to late (Groups 8–9) in northern locations.

Gross photosynthesis was estimated for the fraction of the day with clear (GPc) and overcast (GPo) sky, where daily GP was obtained from their sum; GPc and GPo are given by the following equations, adapted from Doorenbos & Kassam (1979):

$$GPc = (107.2 + 8.604 \times SRo) \times cTc \times (n/N) \quad (2)$$

$$GPo = (31.7 + 5.234 \times SRo) \times cTo \times (1 - n/N) \quad (3)$$

where  $SRo$  is the extraterrestrial solar radiation (MJ/m<sup>2</sup> day), and  $cTc$  and  $cTo$  are dimensionless coefficients associated with the efficiency of the photosynthetic process, being a function of the crop type and its metabolism to atmospheric CO<sub>2</sub> fixation and temperature-dependent. These equations have been used with very good performance for soybean (Battisti & Sentelhas 2015), maize (Andrioli & Sentelhas 2009) and sugarcane (Monteiro & Sentelhas 2014).

The value of  $C_{RESP}$  was 0.5 when average temperature was >20 °C and 0.6 when average temperature

Table 1. Average soybean yield between 1990 and 2011, and yield, area and total production in the 2010/11 growing season in the main Brazilian production states

State	Average yield (kg/ha) (1990–2011)	2011		
		Yield (kg/ha)	Area (million ha)	Production (million tonnes)
Mato Grosso	2778	3222	6.46	20.80
Rondônia	2619	3170	0.13	0.42
Paraná	2599	3393	4.56	15.46
Distrito Federal	2533	3355	0.05	0.18
Goiás	2475	3008	2.57	7.70
Minas Gerais	2374	2899	1.02	2.94
São Paulo	2368	2756	0.49	1.27
Mato Grosso do Sul	2367	2922	1.76	5.08
Santa Catarina	2290	3258	0.46	1.49
Maranhão	2262	2961	0.53	1.57
Tocantins	2243	3012	0.40	1.19
Bahia	2216	3360	1.05	3.51
Piauí	2094	2982	0.38	1.14
Rio Grande do Sul	1880	2875	4.08	11.72
Brazil	2400	3121	24.03	74.82

Source: IBGE (2013).

was  $<20^{\circ}\text{C}$  (Doorenbos & Kassam 1979). The  $C_w$  index was considered as 13%, as recommended by seed companies for reducing losses during the storage process, whereas  $C_H$  was taken as 0.33, obtained from the calibration process with mean actual yield for each location, using the same procedure of Battisti & Sentelhas (2015), and  $C_{LAI}$  was of 0.4693 calculated to a maximum leaf area index of 4 during the crop cycle.

After calculating  $Y_p$ ,  $Y_a$  was estimated by considering the effect of water deficit on crop growth, estimated using the equation presented by Doorenbos & Kassam (1979) and Rao *et al.* (1988), with water deficit sensitivity index ( $K_y$ ) values being calibrated until the lower absolute mean error between estimated and observed yield was observed:

$$Y_a = Y_p \times \prod_{i=1}^n \left( 1 - K_{y_i} \times \left( 1 - \frac{ET_{a_i}}{ET_{c_i}} \right) \right) \quad (4)$$

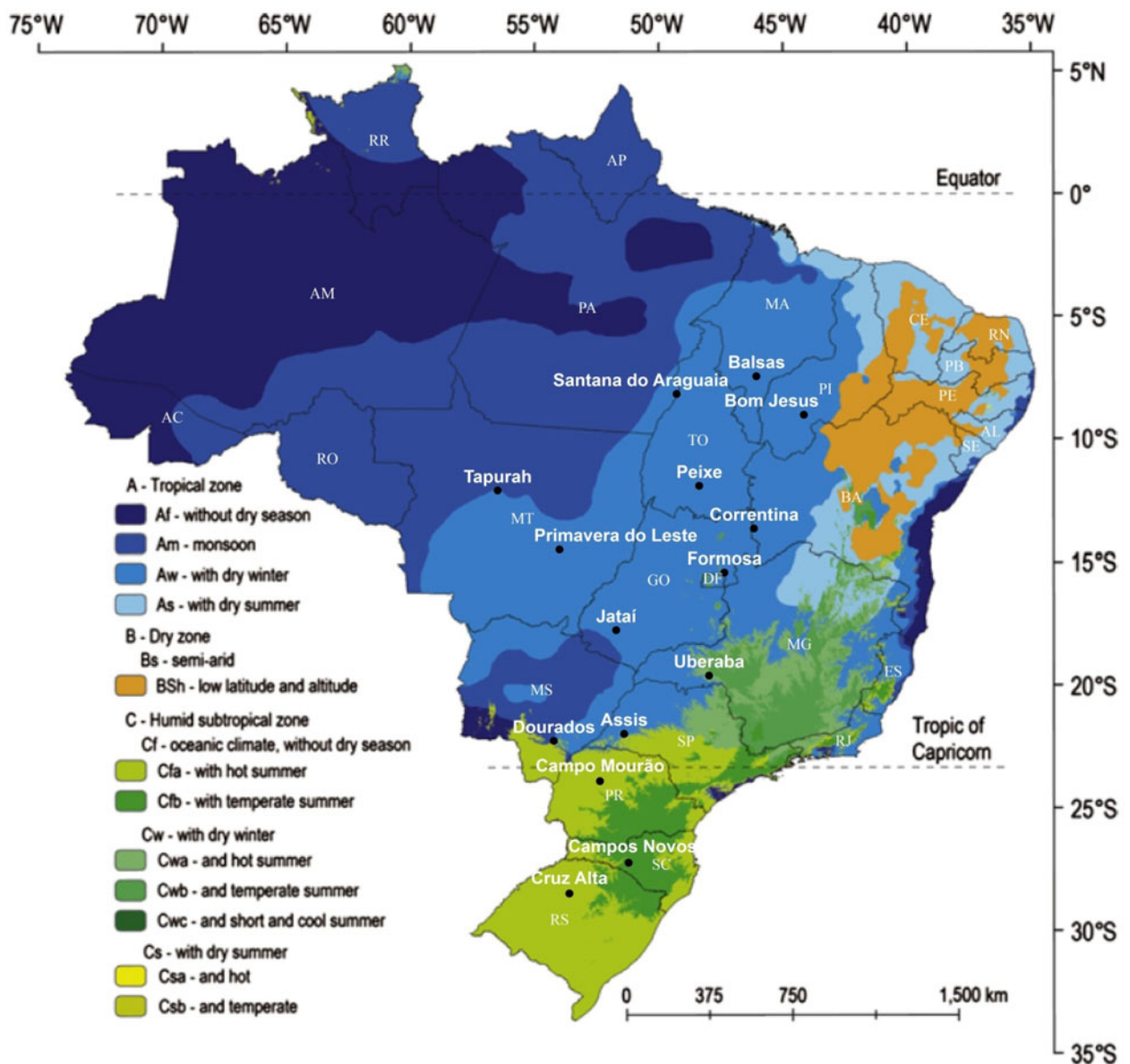
where  $Y_a$  is in kg/ha;  $ET_{a_i}$  is the actual evapotranspiration, determined through the crop water balance (Thorntwaite & Mather 1955), which has inputs of rainfall, maximum crop evapotranspiration and soil water holding capacity; and  $ET_{c_i}$  is maximum crop evapotranspiration, which is the product between reference evapotranspiration, estimated by the

Priestley & Taylor (1972) method, and  $k_c$  for each  $i$  phase, to all  $n$  phenological phases, as follows: establishment ( $K_{C_{S-V2}} = 0.56$ ), vegetative growth ( $K_{C_{V2-R1}} = 1.21$ ), flowering/yield formation ( $K_{C_{R1-R5}} = 1.5$ ) and repining ( $K_{C_{R6-R8}} = 0.9$ ) (Farias *et al.* 2001). Calibrated  $K_y$  for each crop phenological phase were:  $K_{y_{S-V2}} = 0.06$ ;  $K_{y_{V2-R1}} = 0.17$ ;  $K_{y_{R1-R5}} = 0.89$ ;  $K_{y_{R6-R8}} = 0.08$ .

The representative soil type of each location was determined using the maps presented by IBGE (2012). The soil water holding capacity for each type of soil was determined by pedotransfer functions presented by Lopes-Assad *et al.* (2001) and Reichert *et al.* (2009), having as inputs the clay, silt and sand contents.

The calibration process considered 984 actual soybean yield data, whereas the model performance was evaluated with 143 independent actual yield data. For evaluating the performance of the calibrated model the following indices and errors were used: coefficient of determination ( $R^2$ ); agreement index ( $d$ ); mean error ( $ME$ ); mean absolute error ( $MAE$ ); and mean absolute percentage error ( $MAPE$ ) (Willmott *et al.* 1985).

The yield gap was determined from the difference of attainable and actual ( $Y_{aar}$ ) yields in order to identify the yield gap caused by crop management and



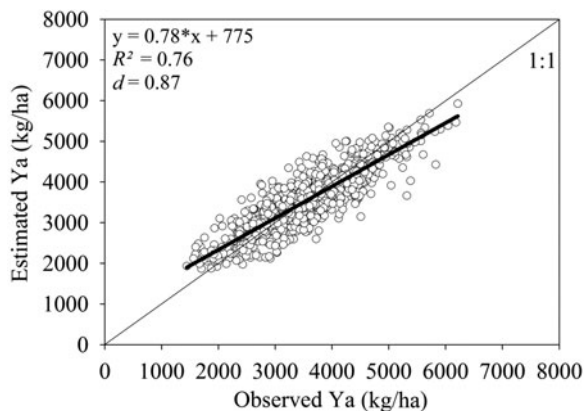
**Fig. 4.** Brazilian locations used in the present study for soybean yield gap estimates and their respective Köppen's climate classification. Adapted from Alvares *et al.* (2013). (Colour online).

between  $Y_p$  and  $Y_a$  to identify the yield gap caused by water deficit. Potential and attainable yields were simulated for the main sowing window of each region (MAPA 2012). The weather data were obtained from the National Water Agency and National Institute of Meteorology, considering maximum and minimum air temperature, effective hours of sunshine and rainfall.

Actual yield were obtained from the Brazilian Geographical and Statistical Institute (IBGE) and Brazilian Food Supply Company (CONAB) for the period between 1980 and 2011. These data had their technological trend removed according to the

procedure presented by Heinemann & Sentelhas (2011). The evaluated locations and their respective states were: Cruz Alta, Rio Grande do Sul; Campos Novos, Santa Catarina; Campo Mourão, Paraná; Assis, São Paulo; Dourados, Mato Grosso do Sul; Uberaba, Minas Gerais; Jataí, Goiás; Formosa, Goiás; Correntina, Bahia; Primavera do Leste, Mato Grosso; Tapurah, Mato Grosso; Peixe, Tocantins; Bom Jesus, Piauí; Santana do Araguaia, Pará; and Balsas, Maranhão (Fig. 4).

The yield gap causes were determined based on the water deficit observed along the simulated crop cycles



**Fig. 5.** Relationship between observed and estimated attainable yields ( $Y_a$ ) for Brazilian soybean cultivars, with groups of maturity ranging from early (Groups 6–7) to late (Groups 8–9).

and by the difference between  $Y_p$  and  $Y_a$ . For the yield gap caused by crop management, expressed by the difference between attainable and actual yields, the main causes were identified through the literature, which make references to the problems faced by soybean growers in different parts of the country.

## RESULTS

### Model test

The results of the yield model calibration process for estimating soybean yield showed a very good performance, presenting good precision ( $R^2 = 0.76$ ) and accuracy ( $d = 0.87$ ). Figure 5 presents the results from the comparison between observed and estimated soybean attainable yields for the independent data set, including different locations, years and sowing dates. The results show that the model can be used to study soybean yield variability in Brazil, with MAE of 284 kg/ha, corresponding to MAPE of 8.4%. The tendency was towards a slight overestimation, with ME of 7 kg/ha. The average estimated yield was 3544 kg/ha while the observed yields averaged 3351 kg/ha.

### Soybean yield gaps in Brazil – magnitude and causes

Yield gaps were estimated with the yields defined as potential, attainable and actual. The probability of occurrence of these yields and the respective yield gaps are presented in Fig. 6 for 15 regions, as averages of 32 years (1980–2011). The results show that in more than half of these years,  $Y_p$  exceeded 4709 kg/ha, while the mean  $Y_a$  was 3428 kg/ha and the mean actual

yield was 3028 kg/ha. For the higher values, potential, attainable and actual yields were greater than 5332, 3866 and 3347 kg/ha, respectively (Fig. 6a), in 0.10 of the years.

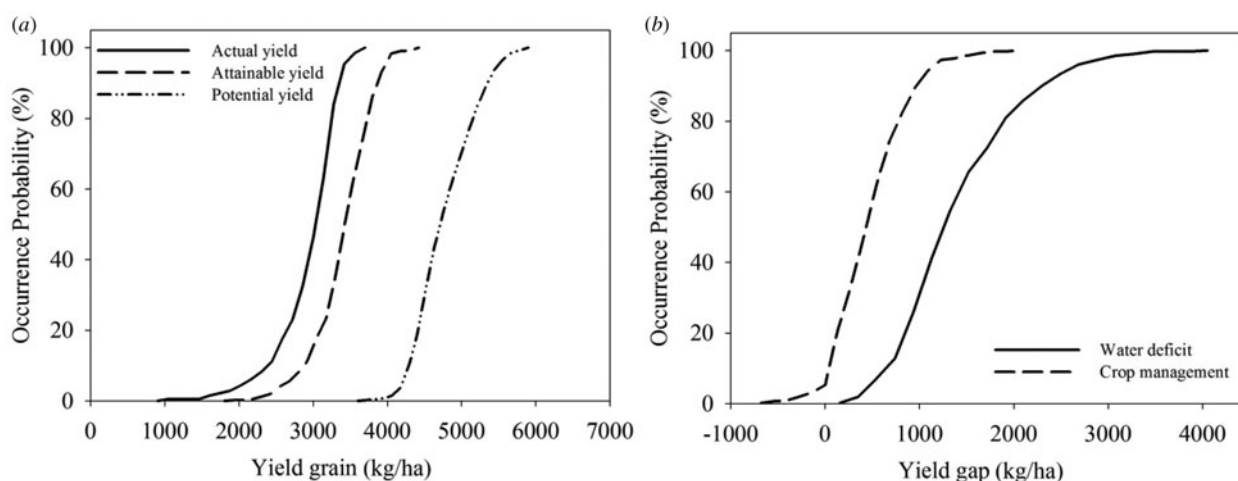
Differences between attainable and actual yields were, on average, 464 kg/ha, which represents the yield gap caused by crop management, while the yield gap caused by water deficit, which is estimated by the difference between  $Y_p$  and  $Y_a$ , was 1378 kg/ha. The probabilities of occurrence of yield gaps are shown in Fig. 6b. The maximum yield gaps reached 2048 and 4053 kg/ha when caused by crop management and by extreme water deficit, respectively. Negative probability values of yield gap by crop management were observed, which may be related to inconsistencies or in the weather data used or in the yields reported by IBGE and CONAB. This kind of problem was also observed by van Ittersum *et al.* (2013), evaluating the yield gaps for maize and wheat at a global level.

In relative terms, the average soybean yield gap was ~42%; ~29% caused by water deficit and ~13% by crop management (Fig. 6). In west Kenya, van Ittersum *et al.* (2013) reported a yield gap of ~69% for rainfed maize, where the greatest difference was assigned to the use of low inputs in production. On the other hand, the yield gap in irrigated maize in Nebraska, USA, using maximum yield as the potential, was only ~11% (Grassini *et al.* 2011), similar to the Brazilian soybean yield gap when considering only crop management. In India, Bhatia *et al.* (2008) found soybean yield gap due to crop management of 54%, and 28% by water deficit, similar to the present results.

Analyzing the data from each one of the 15 locations in Brazil, the results show that  $Y_p$  ranged from 4210 to 5600 kg/ha, with the greatest values occurring in Southern Brazil including Cruz Alta, Campos Novos, Campo Mourão, Dourados and Assis, where  $Y_p$  was >4900 kg/ha as a result of the longer photoperiod and higher solar radiation during the growing season. For the other locations,  $Y_p$  ranged between 4210 and 4900 kg/ha (Fig. 7a).

The two locations evaluated in Mato Grosso state, the main area for soybean production in the country (Primavera do Leste and Tapurah), had lower  $Y_p$  between 4210 and 4550 kg/ha, caused by lower solar radiation and shorter photoperiod. Comparing Cruz Alta, RS (28°37' S) with Primavera do Leste, MT (14°36' S), for soybean sown on 15 November and with a crop cycle of 120 days, the average





**Fig. 6.** Probability of occurrence of actual, attainable and potential soybean yields (a) and causal factors for the yield gap (b), in the fifteen studied locations in Brazil.

extraterrestrial solar radiation is 41.42 and 40.13 MJ/m<sup>2</sup> day, respectively, while average photoperiod is 13.35 and 12.64 h/day.

Cruz Alta had the greatest potential yield, but the lowest Ya (2800–3050 kg/ha) among the 15 locations, which was caused mainly by the water deficit that normally occurs in this region during the grain filling phase. The second range of Ya, between 3050 and 3300 kg/ha, includes the locations of Correntina, Bom Jesus, and Balsas, in North-eastern Brazil, and Assis and Campo Mourão, in the centre-south of the country. The other locations achieved Ya between 3300 and 3800 kg/ha.

Actual yield is additionally affected by crop management, such as sowing uniformity, weeds, insect and disease control and fertilization, among others. It is possible to see the good correlation between attainable and actual yield for many locations, as in Cruz Alta, which again had the lowest actual yields, ranging from 2200 to 2500 kg/ha (Fig. 7c). The locations with highest yields were Jataí and Tapurah in Mid-west Brazil and Santana do Araguaia in the northern region, with average yields ranging from 3100 to 3400 kg/ha. These values are closer to the average actual yields for the states where these locations are, as shown in Table 1.

The yield gaps due to water deficit are presented in Fig. 8. The highest yield gaps were observed mainly in the south, with >2050 kg/ha in Cruz Alta, and between 1600 and 2050 kg/ha in Campo Mourão, Assis and Dourados. Campos Novos was an exception in Southern Brazil, with a yield gap between 1050 and 1600 kg/ha, associated with the altitude of nearly

1000 m a.s.l. At such altitudes, evapotranspiration is lower and rainfall tends to be higher. Tapurah, Jataí, Santana do Araguaia and Uberaba had the lowest yield gaps due to water deficit, between 500 and 1050 kg/ha, due mainly to well-distributed rainfall during the growing season. The other locations presented yield gaps between 1051 and 1600 kg/ha.

The soybean yield gap caused by water deficit depends on the climate of the region as well as its inter-annual variability during soybean growth. As an example of the climate variability and its impact on soybean yield, Fig. 9a shows soybean yields in a neutral year (crop season 2010/11), with yields >1200 kg/ha and with most of the regions having yields >2000 kg/ha. In contrast to this, Fig. 9b shows the crop season of 2011/12, a La Niña year, when rainfall was reduced in Southern Brazil, resulting in yields <1200 kg/ha in the soybean regions of Rio Grande do Sul state. Other regions, such as west of Santa Catarina and Paraná and southwest of Mato Grosso do Sul, were also impacted by La Niña but to a lesser degree.

Although water deficit was the main yield factor causing a gap, other factors can also contribute to yield reduction. This statement is supported by the results presented in Fig. 10, which are from experiments conducted in 23 sites in Southern Brazil by the Pro-Seeds Foundation (2013). From Fig. 10, two conditions can be postulated: one showing that yield can vary substantially (from 2900 to 5000 kg/ha) with the same relative evapotranspiration during the reproductive phase (from 0.65 to 0.70), shown by box (a); and the second is when a similar yield

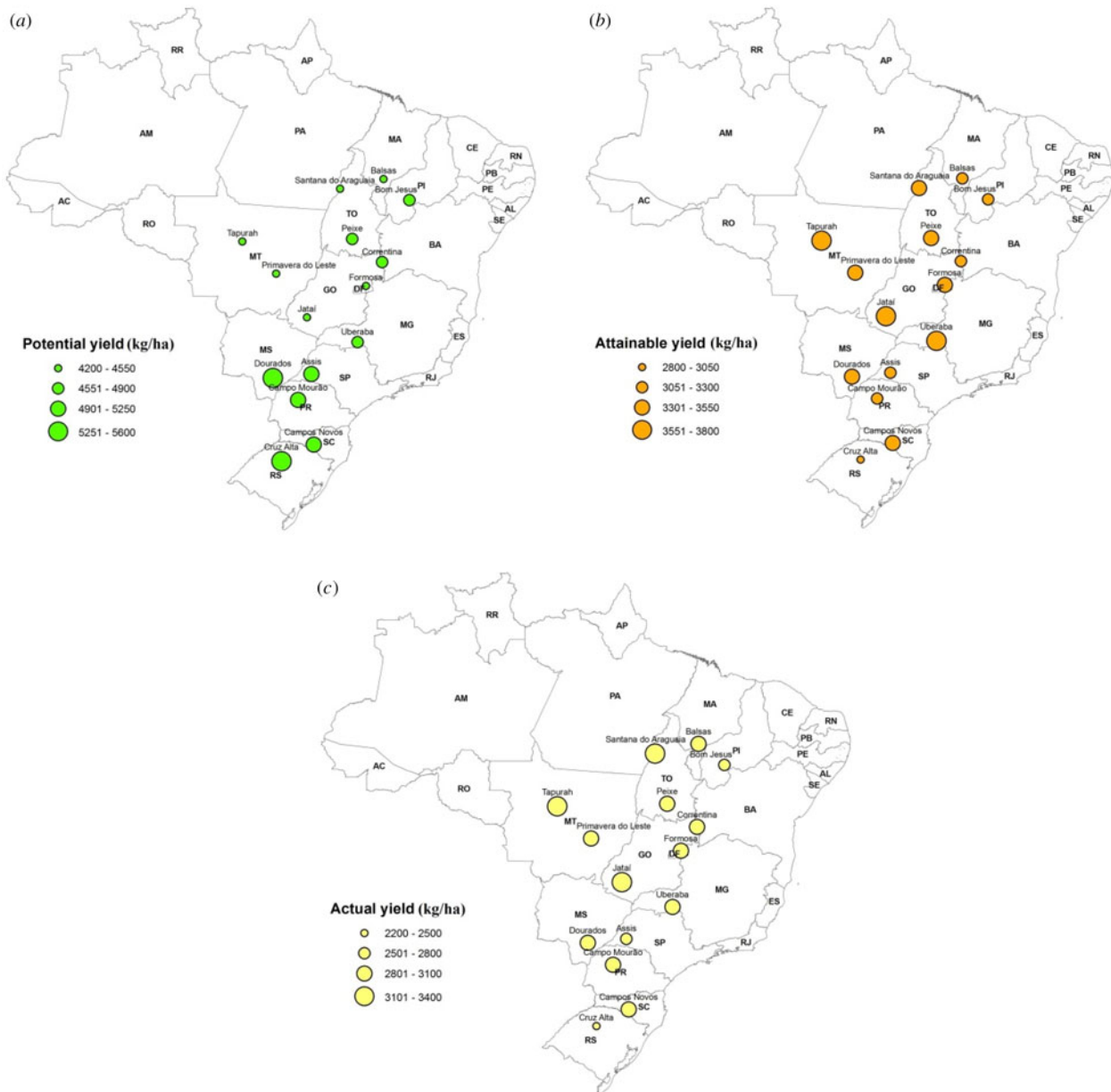


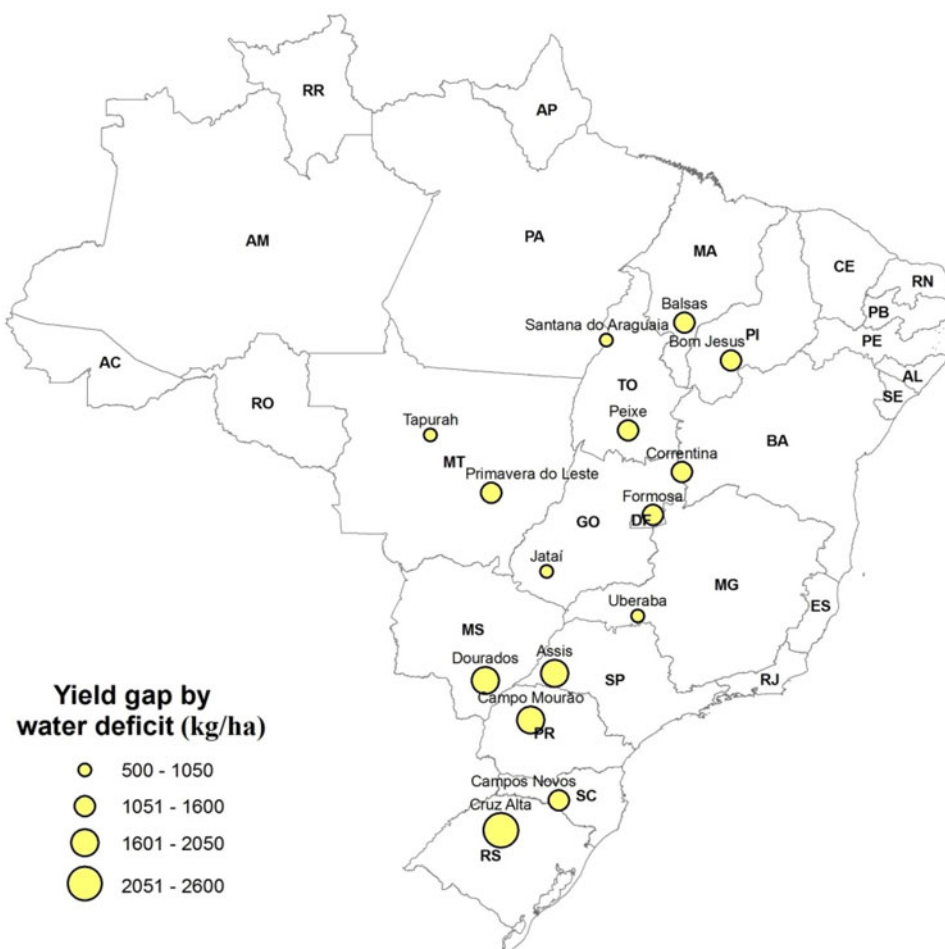
Fig. 7. Potential (a), attainable (b) and actual (c) soybean yields for the main producing regions in Brazil. (Colour online).

(c., 3500 kg/ha) can be obtained in a huge range of relative evapotranspiration in the reproductive phase (from 0.80 to 0.95), as shown by box (b). These results show that crop management can cause variations in soybean yield with the same soil water availability – box (a) – and that crop management, such as sowing date, use of appropriate cultivars, fertilization and disease, pest and weed control, when done in a rational way, can improve crop resilience, making plants more tolerant to water deficit (Sentelhas & Monteiro 2009).

The part of the yield gap caused by crop management was obtained by the difference between

attainable and actual yields. The results show that the greatest gaps were more concentrated in South-central Brazil, with the exception of Campo Mourão (Fig. 11). In the soybean locations in the mid-west, north and north-east regions, the yield gap caused by crop management was <500 kg/ha.

When evaluating the integrated effects of water deficit and crop management on soybean yield gaps (Fig. 12), special attention should be given to Southern Brazil, which had total yield gaps >2000 kg/ha. The same is true for Bom Jesus in North-east Brazil. For the other locations the yield gaps were



**Fig. 8.** Soybean yield gap caused by water deficit in the main producing regions of Brazil. (Colour online).

smaller but always  $>900$  kg/ha, which is a considerable loss for every crop season.

Therefore, the main factor that reduces soybean yield in Brazil is related to in-season weather stresses by water deficit, which is also prevalent in other parts of the world where advanced technology is applied (Bhatia *et al.* 2008; Farias *et al.* 2001; Sinclair *et al.* 2010). Regarding crop management, the main factor reducing yields in the long term could be associated with an imbalance of soil fertility, since soybean is cultivated as a monoculture, as suggested by the studies of Franchini *et al.* (2009) and Hörbe *et al.* (2013). Diversity of crops is an important aspect for improving soil structure, increasing the water and nutrient availability. Pest, disease and weed control is not generally responsible for considerable yield gaps, but the excessive use of agrochemicals reduce financial income and environmental quality; however, attention should be given to the increasing nematode problems in soybean fields, which are

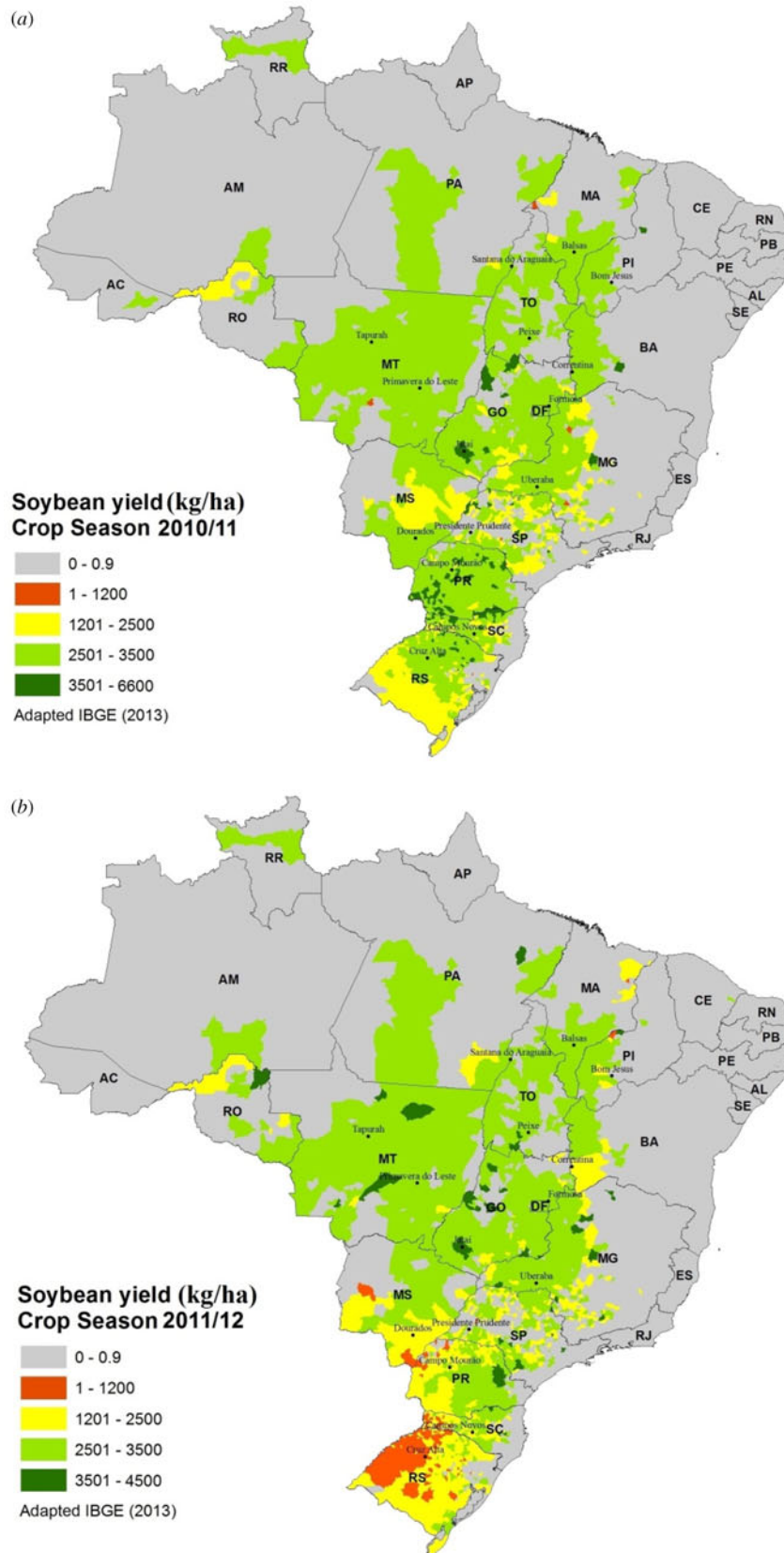
hard control (Matsuo *et al.* 2012), as well as stink bugs, caterpillars (*Chrysodeixis includens*), weeds (*Conyza bonariensis*; *Digitaria insularis*) and Asian rust (*Phakopsora pachyrhizi*).

## DISCUSSION

Possible solutions to reduce soybean yield gaps in Brazil

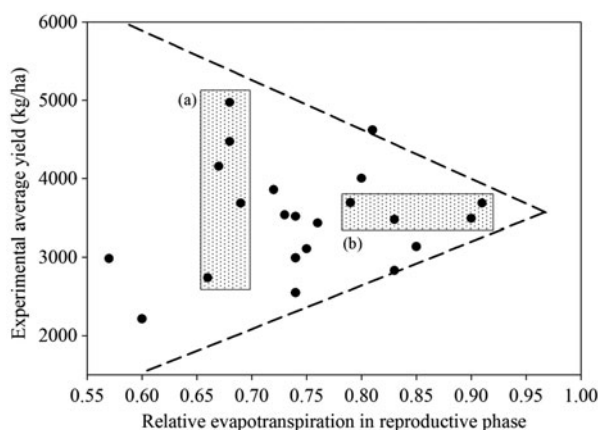
### Irrigation

Soybean is a crop that tolerates water deficit very well when compared with maize, but is sensitive to water stress during yield formation, i.e. flowering and grain filling (Torrion *et al.* 2011). Irrigation could be used during the critical crop phases and in years with reduced rain. This strategy should be considered where Yp and the yield gap from water deficit are greater, as in Cruz Alta, RS.



**Fig. 9.** Soybean yield in the crop seasons of 2010/11 (a) and 2011/12 (b), in Brazil. (Colour online).

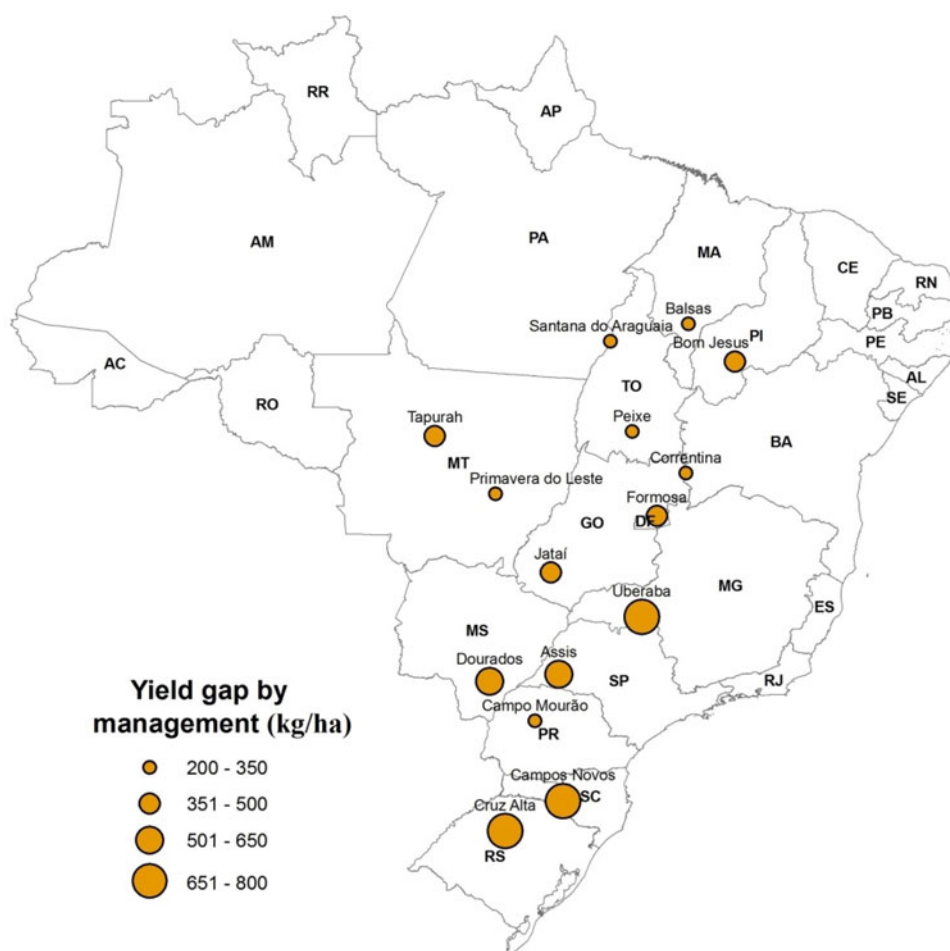




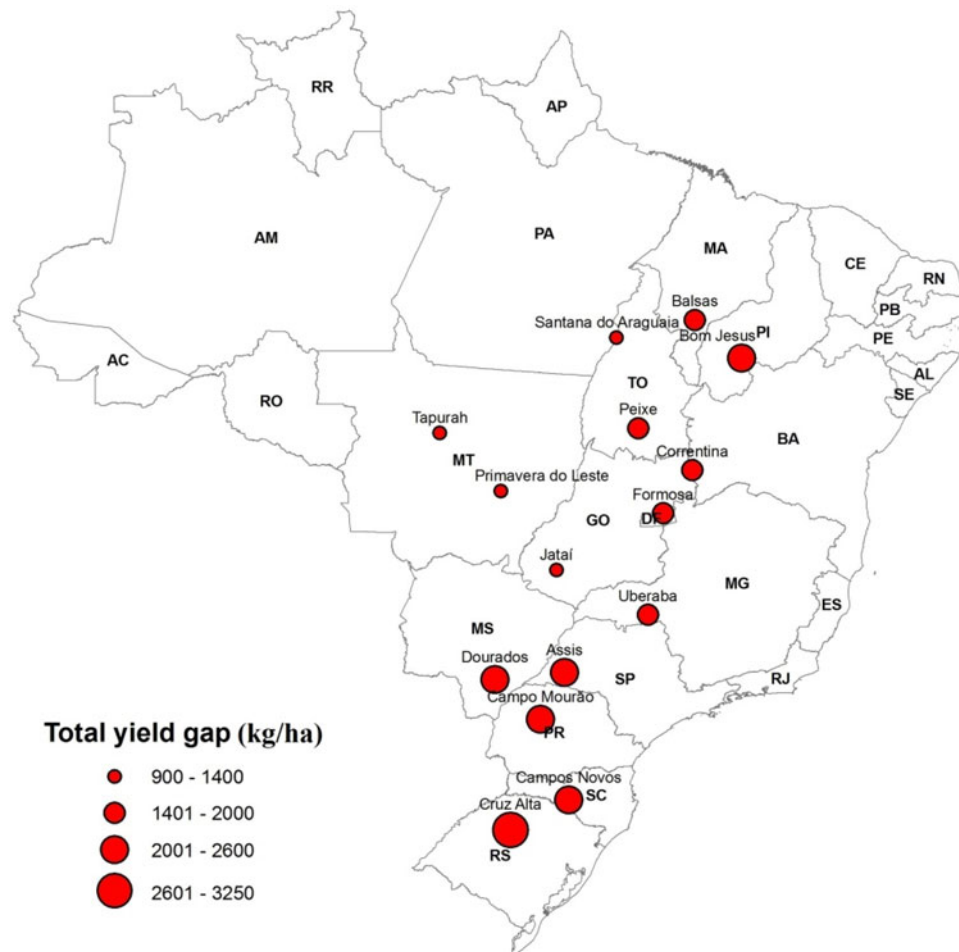
**Fig. 10.** Relationship between relative crop evapotranspiration ( $ET_a/ET_c$ ) in the soybean reproductive phase and experimental average yields for 23 sites in southern Brazil. Source: Adapted from Pro-Seeds Foundation (2013).

Kuss *et al.* (2008) observed yield increases in irrigated over rainfed crops of 26 and 15% for plant densities of 25 and 40 plants/m<sup>2</sup>, respectively: these results emphasized the importance of plant population when considering the use of irrigation as a tool to reduce yield gap. Another important result found by these authors, was that for rainfed conditions the increase of population from 25 to 40 plants/m<sup>2</sup> increased yield by 18%.

In Brazil, the use of irrigation in soybean crops is uncommon, only covering c., 0.05 of the cultivated area. The main limitations to improve the use of this technology in soybean fields are associated with: the bureaucracy of environmental laws, since Brazil does not have a well-defined national irrigation plan; lack of infrastructure regarding water and energy availability; and lack of accessible credit for irrigation (IICA 2008).



**Fig. 11.** Soybean yield gap caused by crop management in the main producing regions of Brazil. (Colour online).



**Fig. 12.** Total soybean yield gap in the main producing regions of Brazil. (Colour online).

### Breeding

Another alternative could be to select soybean cultivars which are more tolerant to water deficit or have higher water use efficiency. For Brazilian soybean cultivars, Battisti & Sentelhas (2015) used a crop simulation model and experimental data to identify four groups of soybean cultivars with different tolerance to water stress. The cultivars more tolerant to water stress presented a lower potential yield, and the less tolerant group had a greater potential yield. In the same way, Gilbert *et al.* (2011) found different limited transpiration rates as a function of vapour pressure deficit for different soybean lineages, so the cultivars could be allocated according to the local soil water availability during the growing season.

Sinclair *et al.* (2010) evaluated the benefits of modifying five soybean traits for water-deficit conditions as rooting depth extension, rate of leaf area development, stomata conductance at high soil water content, maximum transpiration rate and drought-tolerant

nitrogen fixation, for the main production regions in USA; however, they observed that the manipulated traits giving better yields in drought condition do not perform well during a rainy season or in irrigated conditions. For stomatal conductance at high soil water content and reduced maximum transpiration rate, Sinclair *et al.* (2010) showed benefits for most of the regions. The main trait that brought benefits to soybean in a dry season without yield reduction in the rainy season was drought-tolerant nitrogen fixation. The kind of study undertaken by Sinclair *et al.* (2010) is of extreme importance for defining the main soybean cultivar traits that can be selected to reduce the yield gap caused by water deficit under both present and future climate scenarios.

### Sowing date

Agro-climatic zoning and climatic risk zoning for defining the best sowing dates for soybean are also important operational tools used to reduce the yield

gap from water deficit. Climate risk zoning is developed based on historical climate data, where the aim is to define the best suitable sowing dates in order to lower the probability of yield losses due to water deficit during reproductive soybean phases. In Brazil, the Ministry of Agriculture, Livestock and Food Supply (MAPA 2012) defines suitable sowing dates as those at which at least 60% of crop evapotranspiration is covered by water supply during the yield formation phase (flowering and grain filling) in at least 0.80 of years.

Crop simulation models also have great importance for improving yield and reducing gaps, since by simulations it is possible to identify the best sowing dates for a given level of yield, considering not only the most sensitive crop phases to water deficit, but all of them. These models also allow evaluation of crop responses to weather/climate and monitoring of soil water balance for decision making, defining whether the conditions are favourable for pest and disease control, soil management and irrigation.

Specifically for soybean rust, Rodrigues *et al.* (2013b) used a crop simulation model to evaluate the risk of soybean rust occurrence in Southern Brazil and to define the best sowing dates based on that. Another example is the study development by Del Ponte *et al.* (2006, 2011) which estimated soybean rust severity as a function of accumulated rainfall in the last days of the crop cycle, supporting the timing of chemical pest control and for identifying how the ENOS can affect the disease and crop yield. All of these studies are examples of how to use models to improve soybean crop production and reduce the yield gap.

### *Soil improvement*

Besides the use of irrigation and crop management, it is also possible to optimize soil quality by increasing soil water storage and fertility, improving the capacity of plants to explore the soil's deeper resources. This is of major importance for the Brazilian Cerrado where soils have low natural fertility and impeding layers, limiting root growth (Lopes & Guilherme 1994). When the soil exhibits good fertility and favourable physical properties, soybean roots develop well (Torrion *et al.* 2012), reducing the water deficit and increasing availability of nutrients. One step further is precision agriculture, which is another important tool to improve soil fertility, where site-specific fertilization will improve yield and reduce production

costs. Hörbe *et al.* (2013) found an increase in net income and yield when different seed rates were used as a function of the soil fertility zones, classified as high, medium and low. Beyond chemical correction, precision agriculture could also identify problems with soil compaction, which reduces water infiltration and soil water holding capacity.

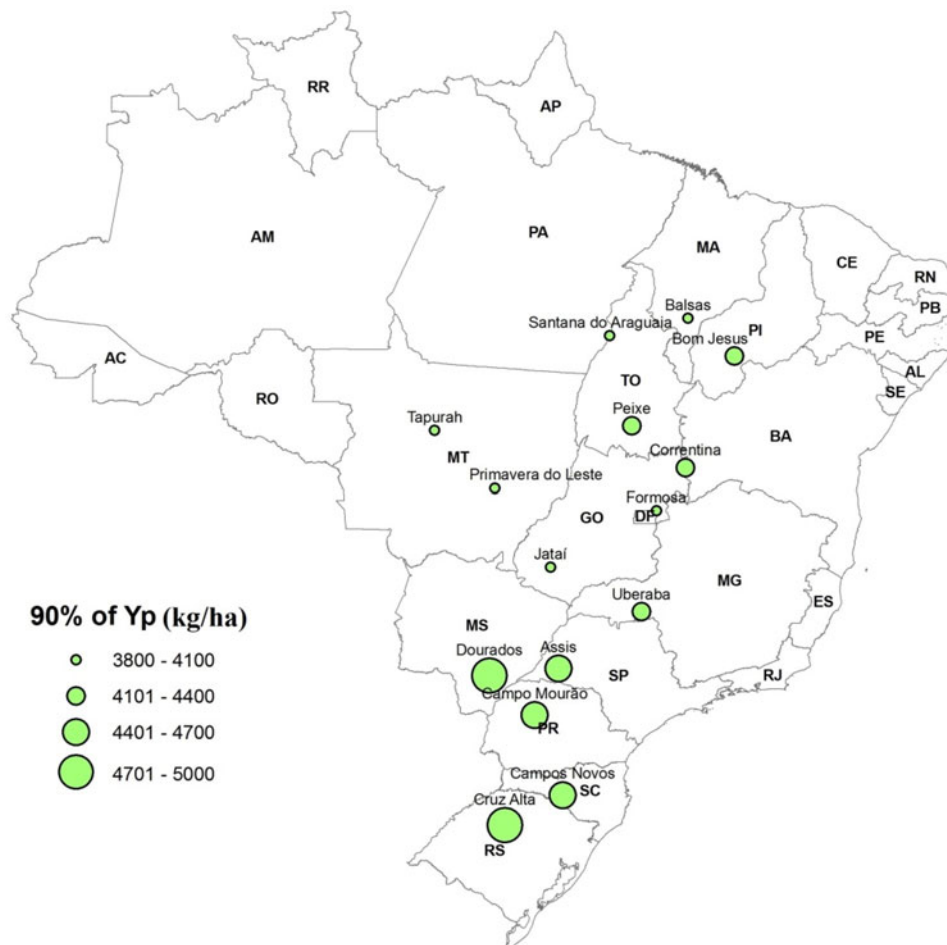
Reduction of soil compaction in order to increase soil hydraulic conductivity, macro porosity and water storage is another way for improving the soil to enhance yields. According to Franchini *et al.* (2009), the soil layers between 0.1 and 0.2 m is the main zone where soil compaction normally occurs; however, when they used crop rotation in Southern Brazil, a reduction of soil compaction and consequent yield improvement were observed in relation to the mono-crop system. Franchini *et al.* (2007) and Hungria *et al.* (2009) highlighted that with crop rotation there is a varied supply of biomass to the soil microbiology both in quantitative and qualitative terms. These managements help to improve root growth and consequently water available to the crop, reducing drought during soybean growth and the yield gap by water deficit.

### *Crop rotation*

An important aspect to improve yield and keep it stable is to encourage the use of crop rotation. There are many benefits for the medium and long term, such as improvements in soil quality, disrupting the dynamics of diseases, pests and weeds, decrease of production costs, yield stability in extreme climatic conditions through use of different crops and cultivars, and wider sowing windows (Franchini *et al.* 2011). According to Franchini *et al.* (2011), the use of many different crops in the same area improves soil biology and makes nutrient cycling and nitrogen fixation more efficient. In tropical environments, no-tillage system benefits include: improved soil structure and porosity, effective erosion control, conservation of soil moisture in the soil surface, lowering of daily maximum soil temperature at soil surface to a level more favourable for plant growth, maintenance for soil organic matter, improved water use efficiency, and reduction of incidences of weeds, diseases and pests (Phillips *et al.* 1980).

### *Dissemination*

Farm experiments can be used to compare alternative crop management practices in a series of farmer's



**Fig. 13.** Possible future soybean yield considering a reduction of the yield gap to a maximum of 10% of potential yield (Yp) for the main producing regions in Brazil. (Colour online).

fields, being the most conceptually straightforward way to show how to improve yield and reduce yield gaps at a regional level. Furthermore, the knowledge on yield-reducing factors and the different ways to overcome them need to be disseminated in various ways, starting from young farmer's education in agricultural colleges and ending with professional field days and agricultural TV programmes.

## CONCLUSION

The results presented in this study show that soybean production in Brazil can be improved rationally without area expansion. There is a huge opportunity to reduce yield gap of this crop by increasing the actual yield through the adoption of different strategies, as described previously. In this way, the yield gap could be reduced to a maximum of 10% of potential yield, with average actual yield achieving >3800

kg/ha in all producing regions (Fig. 13), which is more than the maximum average values obtained now. Such a target is ambitious, but possible if advanced and sustainable technology could be applied.

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## REFERENCES

- ALBERTO, C. M., STRECK, N. A., HELDWEIN, A. B., BURIOL, G. A. & MEDEIROS, S. L. P. (2006). Soil water and wheat, soybean, and maize yields associated to El Niño Southern Oscillation. *Pesquisa Agropecuária Brasileira* **41**, 1067–1075. (in Portuguese).
- ALEXANDRATOS, N. & BRUINSMA, J. (2012). *World Agriculture Towards 2030/2050: The 2012 Revision*. ESA Working Paper no. 12–03. Rome: FAO Agricultural Development Studies Team. Available from: <http://www.fao.org/>



- [docrep/016/ap106e/ap106e.pdf](#) (accessed February 2015).
- ALVARES, C. A., STAPE, J. L., SENTELHAS, P. C., DE MORAES GONÇALVES, J. L. M. & SPAROVEK, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* **22**, 711–728.
- ANDRIOLI, K. & SENTELHAS, P. C. (2009). Brazilian maize genotypes sensitivity to water deficit estimated through a simple crop yield model. *Pesquisa Agropecuária Brasileira* **44**, 653–660.
- BATTISTI, R., SENTELHAS, P. C. & PILAU, F. G. (2012). Agricultural efficiency of soybean, corn and wheat production in the state of Rio Grande do Sul, Brazil, between 1980 and 2008. *Ciência Rural* **42**, 24–30. (in Portuguese).
- BATTISTI, R. & SENTELHAS, P. C. (2015). Drought tolerance of Brazilian soybean cultivars simulated by a simple agrometeorological yield model. *Experimental Agriculture* **51**, 285–298.
- BERLATO, M. A., FARENZENA, H. & FONTANA, D. C. (2005). Association between El Niño Southern Oscillation and corn yield in Rio Grande do Sul State. *Pesquisa Agropecuária Brasileira* **40**, 423–432. (in Portuguese).
- BHATIA, V. S., SINGH, P., WANI, S. P., CHAUHAN, G. S., KESAVA RAO, A. V. R., MISHRA, A. K. & SRINIVAS, K. (2008). Analysis of potential yields and yield gaps of rainfed soybean in India using CROPGRO-Soybean model. *Agricultural and Forest Meteorology* **148**, 1252–1265.
- CASSMAN, K. G. (1999). Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Sciences USA* **96**, 5952–5959.
- DEL PONTE, E. M., GODOY, C. V., LI, X. & YANG, X. B. (2006). Predicting severity of Asian soybean rust epidemics with empirical rainfall models. *Phytopathology* **96**, 797–803.
- DEL PONTE, E. M., MAIA, A. H. N., DOS SANTOS, T. V., MARTINS, E. J. & BAETHGEN, W. E. (2011). Early-season warning of soybean rust regional epidemics using El Niño Southern Oscillation information. *International Journal of Biometeorology* **55**, 575–583.
- DESTRO, D., CARPENTIERI-PÍPOLO, V., DE KIIHL, R. A. S. & DE ALMEIDA, L. A. (2001). Photoperiodism and genetic control of the long juvenile period in soybean: a review. *Crop Breeding and Applied Biotechnology* **1**, 72–92.
- DOORENBOS, J. & KASSAM, A. M. (1979). *Yield Response to Water*. Irrigation and Drainage Paper 33. Rome: FAO.
- FAO (2009). *Global Agriculture Towards 2050. High Level Expert Forum – How to Feed the World in 2050*. Rome: FAO.
- FAO (2013). *FAOSTAT 2013: FAO Statistical Databases*. Rome: FAO. Available from: <http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#anchor> (accessed February 2015).
- FAO (2014). *FAOSTAT: Inputs: Population: Annual Time Series: Population Estimation and Projection*. Rome: FAO. Available from: <http://faostat.fao.org/site/550/DesktopDefault.aspx?PageID=550#l1anchor> (accessed February 2015).
- FARIAS, J. R. B., ASSAD, E. D., DE ALMEIDA, I. R., EVANGELISTA, B. A., LAZZAROTTO, C., NEUMAIER, N. & NEPOMUCENO, A. L. (2001). Characterization of the water deficit risk for soybean in Brazil. *Revista Brasileira de Agrometeorologia* **9**, 415–421. (in Portuguese).
- FRANCHINI, J. C., CRISPINO, C. C., SOUZA, R. A., TORRES, E. & HUNGRIA, M. (2007). Microbiological parameters as indicators of soil quality under various soil management and crop rotation systems in southern Brazil. *Soil and Tillage Research* **92**, 18–29.
- FRANCHINI, J. C., DEBIASI, H., SACOMAN, A., NEPOMUCENO, A. L. & FARIAS, J. R. B. (2009). *Soil Management to Reduce Yield Gap by Drought*. Documentos 314. Londrina: Embrapa Soja. (in Portuguese).
- FRANCHINI, J. C., COSTA, J. M., DEBIASI, H. & TORRES, E. (2011). *The Importance of Crop Rotation for Sustainable Agricultural Production in Paraná*. Documentos 327. Londrina: Embrapa Soja. (in Portuguese).
- GILBERT, M. E., HOLBROOK, N. M., ZWIENIECKI, M. A., SADOK, W. & SINCLAIR, T. R. (2011). Field confirmation of genetic variation in soybean transpiration response to vapor pressure deficit and photosynthetic compensation. *Field Crops Research* **124**, 85–92.
- GRASSINI, P., THORBURN, J., BURR, C. & CASSMAN, K. (2011). High-yield irrigated maize in the Western U.S. Corn Belt: I. On-farm yield, yield potential, and impact of agronomic practices. *Field Crops Research* **120**, 142–150.
- HALL, A. J., FEOLI, C., INGARAMO, J. & BALZARINI, M. (2013). Gaps between farmer and attainable yield across rainfed sunflower growing regions of Argentina. *Field Crops Research* **143**, 119–129.
- HEINEMANN, A. B. & SENTELHAS, P. C. (2011). Environmental group identification for upland rice production in central Brazil. *Scientia Agrícola* **68**, 540–547.
- HOANG, V. N. (2013). Analysis of productive performance of crop production systems: an integrated analytical framework. *Agricultural Systems* **116**, 16–24.
- HOCHMAN, Z., GOBBETT, D., HOLZWORTH, D., MCCLELLAND, T., VAN REES, H., MARINONI, O., GARCIA, J. N. & HORAN, H. (2012). Quantifying yield gaps in rainfed cropping systems: a case study of wheat in Australia. *Field Crops Research* **136**, 85–96.
- HÖRBE, T. A. N., AMADO, T. J. C., FERREIRA, A. O. & ALBA, P. J. (2013). Optimization of corn plant population according to management zones in Southern Brazil. *Precision Agriculture* **14**, 450–465.
- HUNGRIA, M., FRANCHINI, J. C., BRANDÃO-JUNIOR, O., KASCHUK, G. & SOUZA, R. A. (2009). Soil microbial activity and crop sustainability in a long-term experiment with three soil-tillage and two crop-rotation systems. *Applied Soil Ecology* **42**, 288–296.
- IBGE (2009). *Census of Agriculture 2006. Grandes Regiões e Unidades da Federação*. Brasília: Instituto Brasileiro de Geografia e Estatística. (in Portuguese).
- IBGE (2012). *Interactive Maps: Soils*. Brasília: Instituto Brasileiro de Geografia e Estatística. Available from: <http://mapas.ibge.gov.br> (accessed February 2015). (in Portuguese).
- IBGE (2013). *Agricultural Production*. Instituto Brasileiro de Geografia e Estatística. Available from: <http://www.sidra.ibge.gov.br/bda/pesquisas/pam/default.asp?o=18&i=P> (accessed February 2015). (in Portuguese).

- IICA (Instituto Interamericano de Cooperación para a Agricultura) (2008). *Irrigation in Brazil: Situation and Perspectives (A Irrigação no Brasil: Situação e Diretrizes)*. Brasília: Ministério de Integração Nacional. (in Portuguese).
- IPCC (2013). Summary for policymakers. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P. M. Midgley), pp. 3–29. Cambridge, UK: Cambridge University Press.
- KASSAM, A. H. (1977). *Net Biomass Production and Yield of Crops*. Rome: FAO.
- KUSS, R. C. R., KÖING, O., DUTRA, L. M. C., BELLÉ, R. A., ROGGIA, S. & STURMER, G. R. (2008). Plant population and irrigation management strategies in soybean tillage. *Ciência Rural* **38**, 1133–1137. (in Portuguese).
- LIANG, W.-L., CARBERRY, P., WANG, G.-Y., LU, R.-H., LU, H.-Z. & XIA, A.-P. (2011). Quantifying the yield gap in wheat-maize cropping systems of the Hebei Plain, China. *Field Crops Research* **124**, 180–185.
- LOBELL, D. B., CASSMAN, K. G. & FIELD, C. B. (2009). Crop yield gaps: their importance, magnitudes, and causes. *Annual Review of Environment and Resources* **34**, 179–204.
- LOPES, A. S. & GUILHERME, L. A. G. (1994). *Soils in the Cerrado – Managing the Fertility for Agricultural Production*. Technical Bulletin no. 5, 2nd edn. São Paulo: ANDA. (in Portuguese).
- LOPES-ASSAD, M. L., SANS, L. M. A., ASSAD, E. D. & ZULLO, J., JR. (2001). Relationship between water holding capacity and sand content in Brazilian soils. *Revista Brasileira de Agrometeorologia* **9**, 588–596. (in Portuguese).
- MAPA - Ministry of Agriculture, Livestock and Food Supply (2012). *Climate Risk Zoning*. Available from: <http://www.agricultura.gov.br/politica-agricola/zoneamento-agricola/portarias-segmentadas-por-uf> (accessed February 2015). (In Portuguese).
- MATSUO, E., SEDIYAMA, T., OLIVEIRA, R. D. L., CRUZ, C. D. & OLIVEIRA, R. C. T. (2012). Characterization of type and genetic diversity among soybean cyst nematode differentiators. *Scientia Agricola* **69**, 147–151.
- MONTEIRO, L. A. & SENTELHAS, P. C. (2014). Potential and actual sugarcane yield in Southern Brazil as a function of climate conditions and crop management. *Sugar Technology* **16**, 264–276.
- PHILLIPS, R. E., THOMAS, G. W., BLEVINS, R. L., FRYE, W. W. & PHILLIPS, S. H. (1980). No-tillage agriculture. *Science* **208**, 1108–1113.
- PRIESTLEY, C. H. B. & TAYLOR, R. J. (1972). On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review* **100**, 81–92.
- Pro-Seeds Foundation (2013). *Cultivar Trials Experiments: Soybean*. Passo Fundo, Brazil: Pro-Seeds Foundation. Available from: <http://fundacaoprosementes.com/?menu=ensaiodecultivares&submenu=soja#id> (accessed January 2013). (in Portuguese).
- RABBINGE, R. (1993). The ecological background of food production. In *Crop Protection and Sustainable Agriculture* (Eds D. J. Chadwick & J. Marsh), pp. 2–29. Ciba Foundation Symposium 177. Chichester, UK: John Wiley.
- RAO, N. H., SARMA, P. B. S. & CHANDER, S. (1988). A simple dated water-production function for use in irrigated agriculture. *Agricultural Water Management* **13**, 25–32.
- REICHERT, J. M., ALBUQUERQUE, J. A., KAISER, D. R., REINERT, D. J., URACH, F. L. & CARLESSO, R. (2009). Estimation of water retention and availability in some soils of Rio Grande do Sul state, Brazil. *Revista Brasileira de Ciência do Solo* **33**, 1547–1560.
- RODRIGUES, G. C., MARTINS, J. D., DA SILVA, F. G., CARLESSO, R. & PEREIRA, L. S. (2013a). Modelling economic impacts of deficit irrigated maize in Brazil with consideration of different rainfall regimes. *Biosystems Engineering* **116**, 97–110.
- RODRIGUES, R. A., JULIATTI, F. C., PEDRINI, J. E., FERNANDES, J. M. C., JUSTINO, F. B., HEINEMANN, A. B., FRAISSE, C. W., FARIAS, J. R. B., PAVAN, W., COSTA, L. C., VALE, F. X. R. & REZENDE, A. A. (2013b). Asian soybean rust: modeling the impact on soybean grain yield in the Triângulo Mineiro/Alto Paranaíba region, Minas Gerais, Brazil. *Bioscience Journal* **29**, 264–279.
- SENTELHAS, P. C. & MONTEIRO, J. E. B. A. (2009). Agrometeorology of Crops: information for sustainable agriculture. In *Agrometeorologia dos Cultivos: O Fator Meteorológico na Produção Agrícola* (Ed. J. E. B. A. Monteiro), pp. 3–12. Brasília: INMET. (in Portuguese).
- SINCLAIR, T. R., NEUMAIER, N., FARIAS, J. R. B. & NEPOMUCENO, A. L. (2005). Comparison of vegetative development in soybean cultivars for low-latitude environments. *Field Crops Research* **92**, 53–59.
- SINCLAIR, T. R., MESSINA, C. D., BEATTY, A. & SAMPLES, M. (2010). Assessment across the United States of the benefits of altered soybean drought traits. *Agronomy Journal* **102**, 475–482.
- THORNTHWAITE, C. W. & MATHER, J. R. (1955). *The Water Balance*. Publications in Climatology no. 8. New Jersey, USA: Drexel Institute of Technology.
- TORRION, J., SETIYONO, T. D., CASSMAN, K., SPECHT, J. (2011). Soybean phenology simulation in North-Central United States. *Agronomy Journal* **103**, 1661–1667.
- TORRION, J., SETIYONO, T. D., CASSMAN, K., FERGUSSON, R. B., IRMAK, S. & SPECHT, J. (2012). Soybean root development relative to vegetative and reproductive phenology. *Agronomy Journal* **104**, 1702–1709.
- VAN ITTERSUM, M. K. & RABBINGE, R. (1997). Concepts in production ecology for analysis and qualification of agricultural input-output combinations. *Field Crops Research* **52**, 197–208.
- VAN ITTERSUM, M. K., CASSMAN, K. G., GRASSINI, P., WOLF, J., TITTONELL, P. & HOCHMAN, Z. (2013). Yield gap analysis with local to global relevance – A review. *Field Crops Research* **143**, 4–17.
- WILLMOTT, C. J., ACKLESON, S. G., DAVIS, R. E., FEDDEMA, J. J., KLINK, K. M., LEGATES, D. R., O'DONNELL, J. & ROWE, C. M. (1985). Statistics for the evaluation and comparison of models. *Journal of Geophysical Research: Oceans* **90**, 8995–9005.