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ABSTRACT

Favorable climate and soils for rainfed crop production, together with a relatively low population density, results in 70–90% of Argentina grain production being exported. No assessment to date has tried to estimate the potential for extra grain production for soybean, wheat and maize, which account for 78% of total harvested area, by yield gap closure on existing cropland area and its impact at a global scale. The objectives of this paper are (i) to estimate how much additional grain could be produced without expanding crop area by closing yield gaps in Argentina, (ii) to investigate how this production and yield gaps varies across regions and years, and (iii) to analyze how these inter-annual variations are related to El Niño—Southern Oscillation phenomenon (ENSO). Production increase on existing crop area was assessed for soybean, wheat and maize by quantifying the yield gap (Yg), that is, the difference between water-limited yield potential (Yw) and actual yield (Ya). A bottom-up approach was followed to estimate Yw and Yg, in which these parameters were first estimated for specific locations in major crop producing areas and subsequently up-scaled to country level based on spatial distribution of crop area and climate zones. Locally-calibrated crop simulation models were used to estimate Yw at each selected location based on long-term weather data and dominant soil types and management practices. For the analyzed period, the national level Yg represented 41% of Yw for both wheat and maize and 32% of the Yw for soybean. If farmers had closed Yg from these levels to 20% of Yw, Argentina could have increased soybean, wheat and maize production by a respective 7.4, 5.2, and 9.2 Mt, without expanding cropland area. This additional production would have represented an increase of 9%, 4%, and 9% of soybean, wheat, and maize global exports. This potential grain surplus was, however, highly variable because of the ENSO phenomenon: attainable soybean production was 12 Mt higher in favorable “El Niño” years compared with unfavorable “La Niña” years. Interestingly, Yg tended to be higher in wet years, suggesting that farmers do not take full advantage of years with favorable conditions for rainfed crop production. Regional variation in Yg was found in Argentina highlighting the usefulness of this work as a framework to target research and, ultimately, reduce gaps in areas where current yields are well below their potential.

1. Introduction

Crop production needs to increase 60% by 2050 to cope with increasing food demand (Alexandratos and Bruinsma, 2012). Production increase can be achieved by expansion of current crop area, higher yield per unit area, or both (Bruinsma, 2009). Furthermore, yield increases per unit area can be achieved through increases of yield potential (Yp) and/or through reductions of yield gaps (Yg) (Fischer et al., 2014). Yp is defined as the yield of a cultivar when grown in an environment to which it is adapted, with nutrients and water non-limiting and with biotic stresses effectively controlled (Evans, 1993; Van Ittersum and Rabbinge, 1997; Evans and Fischer,

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1999). Hence, Yp is determined by solar radiation, temperature, carbon dioxide concentration, and crop physiological attributes governing light interception, conversion into biomass, and partition into the harvestable organs. In rainfed cropping systems, water-limited yield potential (Yw) is determined also by water supply amount and distribution, and soil and landscape properties influencing water availability, such as soil available water holding capacity and terrain slope (Lobell et al., 2009; Van Ittersum et al., 2013). When water supply is not sufficient to satisfy crop water requirements, Yg is estimated as the difference between Yw and actual farm yield (Ya) (Van Ittersum et al., 2013). The size of Yg can be taken as a proxy for the current unexploited grain production capacity (Cassman et al., 2003; Lobell et al., 2009). In turn, the gap between Yp and Yw, hereafter called 'water limitation index' (WLI), provides a measure of the degree to which crops are limited by water.

Detailed descriptions of weather, soils, and cropping systems of Argentina can be found in Hall et al. (1992), Calviño and Monzon (2009) and Satorre (2011). Crop production area in Argentina occupies *ca.* 32 Mha. Major crops are soybean, wheat and maize, accounting for 78% of total crop area (FAOSTAT and FAO, 2015). Argentina has a favorable temperate climate for rainfed crop production, with total annual rainfall that ranges, across cropping regions, from 600 (south-west) to 1400 mm (north-east). Most of Argentine crop area is under the influence of El Niño-Southern Oscillation phenomenon (ENSO). The "El Niño" phase is reflected in an increase in spring/summer rainfalls and higher summer crops yields, while the opposite occurs with "La Niña" events (Podestá et al., 1999; Iizumi et al., 2014). Dominant soils correspond to the Mollisols order, without impedances to crop rooting, except for some regions where a caliche layer limits rooting depth.

Argentine cropping systems have experienced important changes over the last 20 years. Crop yields have increased rapidly (28, 40 and 128 kg ha^{-1} y^{-1} for soybean, wheat and maize, respectively) driven by a wide adoption of no-till systems, increasing amounts of commercial fertilizers, and development of herbicide- and insect-resistant crop varieties with high yield potential (Satorre, 2011; Grassini et al., 2013; F.H. Andrade et al., 2015). At the same time, expansion in cropping area has occurred mainly in areas that were previously used for livestock production in the Pampas region as well as at the expense of natural forested ecosystems in the northern region, which results in growing concerns about environmental footprint (Viglizzo et al., 2011a; Volante et al., 2012; Lambin et al., 2013). Therefore, robust yield-gap analyses can help to determine areas with greatest potential for grain production increase on existing cropland area, and its consequent impact at country level. Likewise, yield-gap assessment also provides the foundation for future studies on crop intensification, land use change, climate change impact, and assessment of irrigation expansion.

Argentina is the third soybean exporter country, first world exporter of soybean derivatives (cake, oil and biodiesel), and respective second and sixth exporter of maize and wheat.[1] Since its internal food demand is expected to remain flat in the future, any future increase in crop production in Argentina will result in a parallel increase in exports (Alexandratos and Bruinsma, 2012). While most yield-gap assessments to date are global studies with limited local relevance, as pointed by Van Ittersum et al. (2013), or are focused on low-input subsistence systems without access to technology, markets, and extension services (Fermont et al., 2009; Waddington et al., 2010; Tittonell and Giller, 2013; Kassie et al., 2014), no attention has been paid to major non-subsidized exporter countries like Argentina. On the other hand, climate variability has a clear influence on crop production, world market supplies, and commodity prices, as it happened in 2007 (Piesse and Thirtle, 2009; Trostle, 2010; Iizumi et al., 2014). Hence, an analysis of how much extra grain a major net exporter country can produce on its existing crop area and how Ya and Yg are affected by climate variability is novel and crucial to assess future grain export/import scenarios and is relevant to global food security.

In the present study, well-calibrated crop simulation models, coupled with high-quality weather, soil, and crop management data, were used to assess Yg of soybean, wheat, and maize in Argentina, following the protocols of the Global Yield Gap Atlas project (Grassini et al., 2015; Van Bussel et al., 2015, http://www.yieldgap.org/methods). Yg were estimated for specific locations in major producing areas and results were up-scaled to climate zones and country levels. Specific objectives of this work were: (i) to quantify the potential for crop production increase in Argentina through closure of existing Yg on current cropland area, (ii) to analyze the regional and inter-annual variability of attainable crop production and Yg, and (iii) to evaluate the attainable crop production as related to the ENSO phenomenon.

2. Materials and methods

2.1. Data sources and selection of weather stations

Data on soybean, wheat and maize crop harvested area and average Ya were retrieved for each department (*i.e.*, the smallest administrative unit in Argentina, average size *ca.* 4000 km^2) from the Argentine Agricultural Ministry (http://www.siia.gov.ar/). Only data for the 2006–2012 time period was used in order to account for the recent expansion in crop area during the last two decades as reported by Viglizzo et al. (2011a), and to avoid the steep trends in average Ya as recommended by Van Ittersum et al. (2013). Indeed, analysis of sequential average Ya starting from the most recent year and gradually including more years back in time indicated that 7 years were appropriated for robust estimations of average Ya and its variation, with an adequate control of technological changes (Supplementary Fig. 1). Previous assessment of crop production statistics quality in Argentina indicated reasonably good accuracy (Sadras et al., 2014). Only rainfed crops were accounted for in the present study as irrigated area accounts for <3% of area sown with the three crops (Siebert et al., 2013).

Selection of data sources and quality control followed the Global Yield Gap Atlas guidelines (Grassini et al., 2015; http://yieldgap.org/methods). Daily maximum and minimum temperature and precipitation data were derived from INTA (National Institute for Agricultural Technology; http://siga2.inta.gov.ar/) and SMN (National Weather Service; http://www.smn.gov.ar/) weather stations. SMN and INTA weather stations have a large number of consecutive missing values for daily solar radiation data. Hence, data from NASA-POWER (http://power.larc.nasa.gov/) were used as source of daily incident solar radiation. Recent evaluations of the NASA-POWER solar radiation data indicate very good agreement with measured solar radiation data in areas with flat topography (White et al., 2011; Van Wart et al., 2013a). Similar results were found for cropping regions in Argentina (n = 18,375 daily observations, Supplementary Fig. 2). Complete weather records for the 1983–2012 period were obtained by combining temperature and precipitation from INTA and SMN weather stations and solar radiation from NASA-POWER data. The number of years used for the simulations was appropriate for robust estimation of average Yw and its variability (Grassini et al., 2015). No consistent trend in temperature and precipitation was detected in Argentina within the period used for the simulations (Fernández-Long et al., 2013). Qual-

[1] Based on 2006–2011 statistics from FAO (2015). It Includes flour as wheat equivalents.

ity control and filling/correction of weather data for the targeted weather stations was performed based on correlations between the target weather station and two adjacent weather stations following Hubbard et al. (2007). The number of corrections/filled data after the quality control procedure was always lower than 3% for all variables.

Following Van Bussel et al. (2015), weather stations used for this study, hereafter called reference weather stations (RWS), were selected based on crop-specific harvested area within a buffer zone area of 100 km radius centered on each RWS and clipped by the climate zone (CZ) where the RWS was located. Each CZ corresponds to a particular combination of growing degree days, aridity index, and temperature seasonality (Van Wart et al., 2013c). RWS were iteratively selected starting with the one with the greatest harvested area coverage until reaching *ca.* 50% of crop-harvested area and more than 70% coverage by the CZ where the RWS were located.

Dominant soil series were identified for each RWS buffer based on data provided by the Soil Institute of INTA (http://geointa.inta.gov.ar/). Dominant soil series (two to three per RWS) were selected based on (i) province-level soil maps (1:50,000 and 1:100,000), and (ii) producer's preference for growing certain crops in best soils (*cf.* Section 2.3). Functional soil properties required to run crop simulation models (*e.g.*, field capacity and permanent wilting point) were derived from soil series descriptions following Ritchie and Crum (1988), after the revisions made by Gijsman et al. (2003). Maximum rooting depth for wheat, maize and soybean was set at 1.8 m except for those locations where a caliche layer restricts root growth (Dardanelli et al., 1997). A complete list of the soils used at each RWS, and specific soil properties, are available on Supplementary Table 1.

2.2. *Crop simulation models used for estimations of yield potential and water-limited yield potential*

Simulations were performed using CERES-Maize, CERES-Wheat and CROPGRO-Soybean models embedded in DSSAT v 4.5 (Jones et al., 2003; Hoogenboom et al., 2010). Genetic coefficients were derived from Mercau et al. (2007, 2014), Monzon et al. (2007, 2012), and unpublished data from well-managed experiments. The three models were evaluated on their performance to simulate Yp and Yw by comparison of model simulated yields against measured yields from well-managed rainfed and irrigated field experiments that explore a wide range of sowing dates, sites, years, and water availability (Fig. 1). The agreement between observed and simulated data was assessed through the root mean square error, expressed as percentage of observed mean (*V*), and its components (Kobayashi and Salam, 2000). Measured inaccuracy in simulated yield was fairly low for the three models (Fig. 1).

2.3. *Simulated cropping systems*

Data on crop management practices (*e.g.*, sowing date, cultivars and plant population density) do not exist or are not publicly available for cropping systems in Argentina. Hence, crop management practices for each RWS were retrieved from local agronomists. One renowned agronomist was identified per RWS and asked to provide all management practices required for simulation of Yp and Yw. Requested information included: dominant crop sequences, soil type, sowing dates, cultivar name and maturity, and plant population density (Supplementary Table 2). In order to account for differences in initial soil water at sowing among years, the entire crop sequence was simulated, assuming 50% of plant available soil water in the first year of the time series. However, at few locations characterized by erratic soil water recharge during fallow (Rafaela and Pilar), producers will sow wheat only in those fields with ≥50% of available soil water. Hence, wheat simulations at these

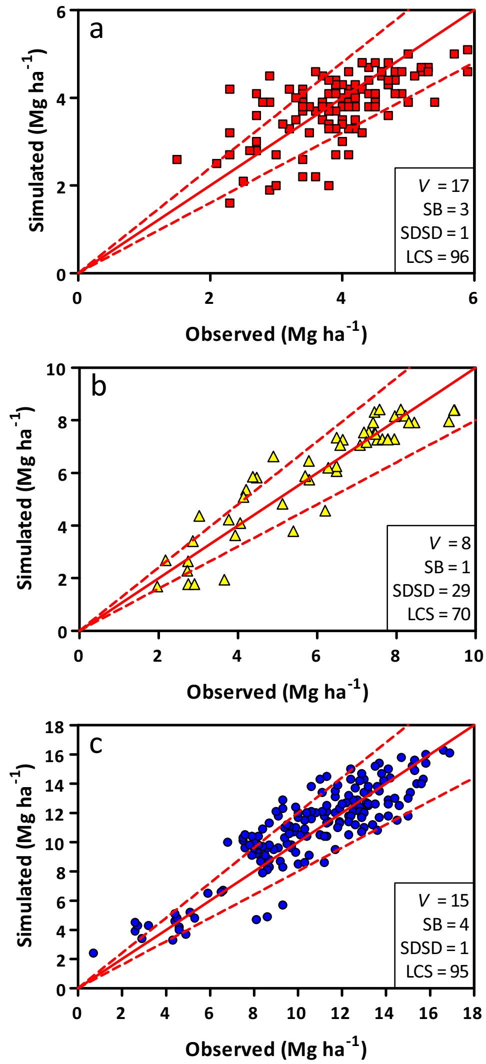

Fig. 1. Comparison of simulated and observed crop yields data for (a) soybean, (b) wheat, and (c) maize. The solid red line represents $y = x$, and the dashed red lines represents $y = x \pm 20\%$. The root mean square error expressed as percentage of observed mean (*V*), and its components: squared bias (SB), squared difference between standard deviations (SDSD), and lack of correlation weighted by the standard deviation (LCS), expressed as percentage of mean squared error, are shown in inset. Genetic coefficients and data points used for the model evaluation were obtained from Mercau et al. (2007, 2014) and Monzon et al. (2007, 2012) and unpublished well-managed experiments.

locations assumed 50% of available soil water at sowing for those cases in which this value was <50% in order to portray farmer's choice of growing wheat only in fields with a reasonable level of stored soil water. The simulated crop sequences were: (i) 2-year soybean–maize, (ii) 2-year soybean–soybean (*i.e.*, continuous soybean), and (iii) 2-year soybean–wheat/soybean double crop, except for Pigüé, where low summer rainfalls constrain crop sequences to: (i) 2-year soybean–soybean and (ii) 2-year wheat–soybean. Separate simulations were performed for potential (Yp) and water-limited conditions (Yw), assuming no limitations to crop growth by nutrients and pests. Atmospheric CO_2 concentration was set constant at 380 ppm.

2.4. *Upscaling method*

Following Van Bussel et al. (2015), each simulated crop sequence – soil type combination was weighted by their relative contribution to the crop-specific harvested area within the RWS buffer to

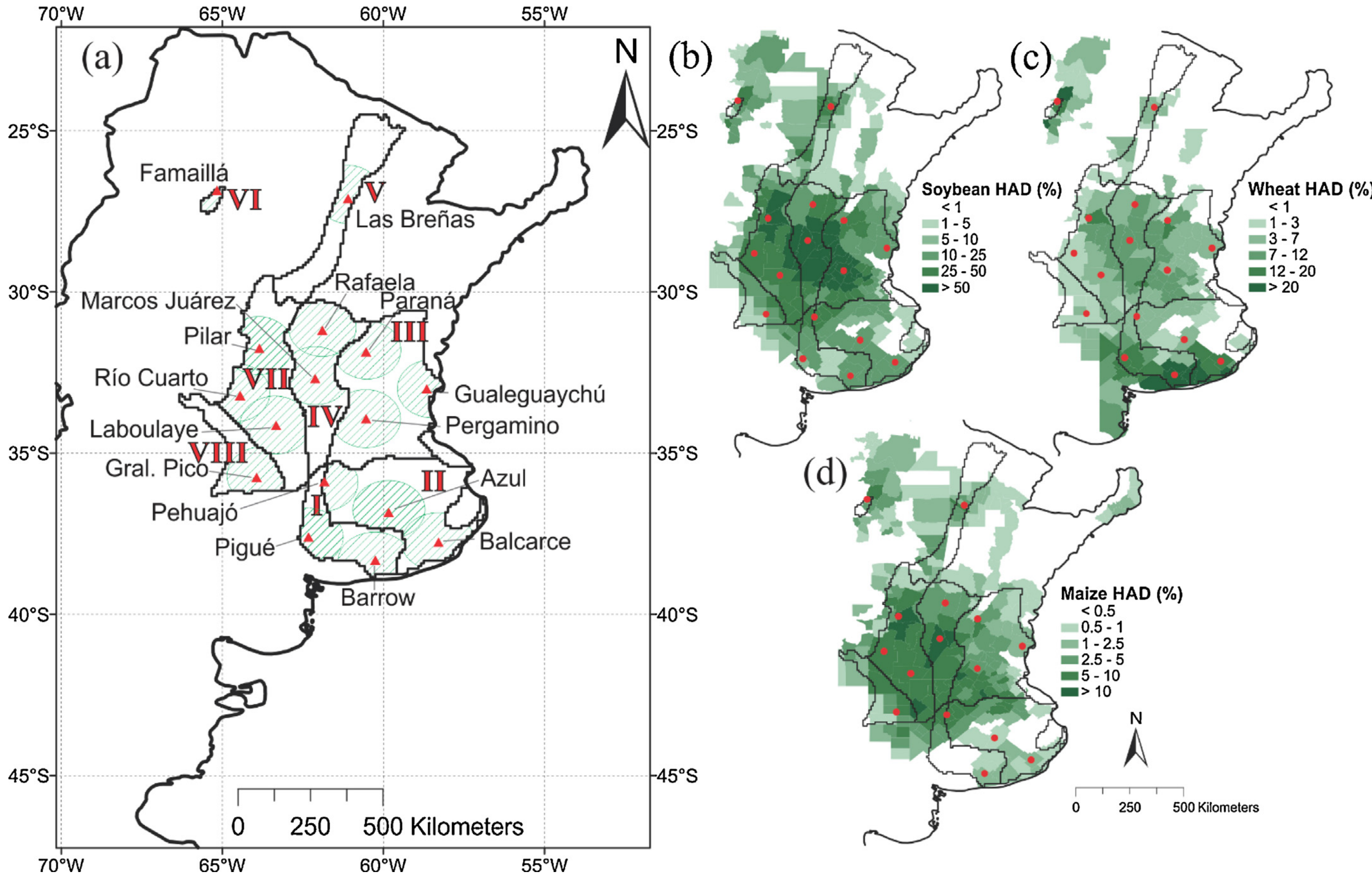

Fig. 2. Maps of Argentina showing (a) selected climate zones (designated by Roman numerals within delineated climate zones), reference weather stations (closed triangles), and buffer zones (hatched areas); and (b) soybean, (c) wheat, and (d) maize average harvest area density per department (HAD, % of total department area) for the 2006–2012 time period.

retrieve averages Yw and Yp. For soybean, separate averages were calculated for single soybean (*i.e.*, a full-season soybean crop) and soybean as the second crop of a double cropping sequence (*i.e.*, soybean sown immediately after harvest of a winter cereal crop). Annual Ya was calculated for each RWS based on the Ya reported for the departments located within the RWS buffer and relative contribution of each department to total crop-specific harvested area within the RWS buffer. Finally, Yp, Yw, and Ya were upscaled to CZ and country levels, based on the relative contribution of each RWS to total crop-specific harvested area. For all spatial scales (*i.e.*, RWS, CZ, and country), Yg was calculated as the difference between Yw and Ya, and also expressed as percentage of Yw. The degree to which crops are limited by water, *i.e.*, the WLI, was calculated as the difference between Yp and Yw and expressed as percentage of Yp.

2.5. National estimation of attainable crop production and ENSO phenomenon

Attainable yield was estimated to be 80% of water-limited yield because farmers' yields tend to plateau when they reach 75–85% of Yp or Yw (Cassman et al., 2010; Van Ittersum et al., 2013; Sadras et al., 2015). Attainable crop production (ACP) of Argentina was calculated as follows:

$$ACP = (Yw \times 0.8) \times Area$$

where area is the crop-specific harvested area of the last (2011/12) cropping season analyzed.

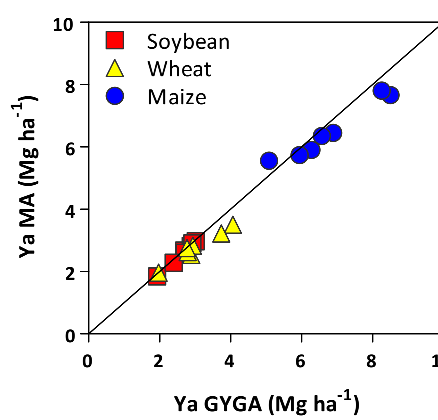

Fig. 3. National average actual yields (Ya) reported by the Argentine Agricultural Ministry (MA, Mg ha^{-1}) as a function of national Ya estimated through the upscaling method of the Global Yield Gap Atlas Protocol followed in the present study (GYGA, Mg ha^{-1}) for each of the 2005/06 to 2011/12 crop seasons. The solid line represents *y* = *x*.

In order to assess influence of the ENSO phenomenon on Argentine Ya, Yw and ACP, cropping seasons were categorized in ENSO phases: Neutral, El Niño (typically wet years), and La Niña (typically dry years), based on the Oceanic Niño Index (ONI) of the Climate Prediction Center of NOAA's National Weather Service (2015). Yw and ACP differences between ENSO phases were evaluated using non-parametric tests (Kruskal–Wallis and Levene's tests), while the effects on Ya were assessed by analyzing the residuals obtained from the regression analysis between Ya and year

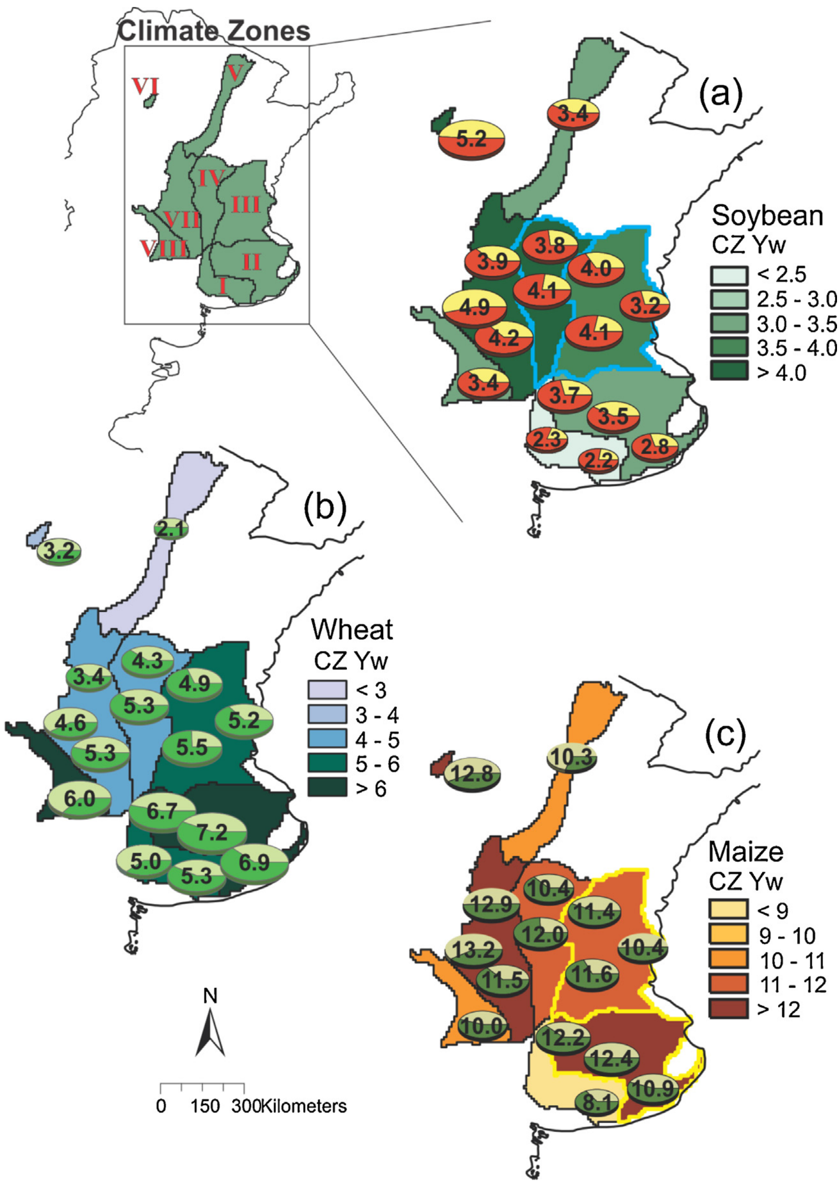

Fig. 4. Water-limited yield potential (Yw, Mg ha^{-1}) for CZ level (colored areas) and reference weather station level (pie charts, with size proportional to Yw level) for (a) soybean, (b) wheat and (c) maize. Actual yields (dark color) and yield gaps (light color) are shown, both relative to the Yw (in numbers), in each pie chart. Borders of the CZs where El Niño—Southern Oscillation phenomenon had a significant effect on Yw are highlighted in light blue (a) and yellow (c) (Kruskal–Wallis test, $P < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

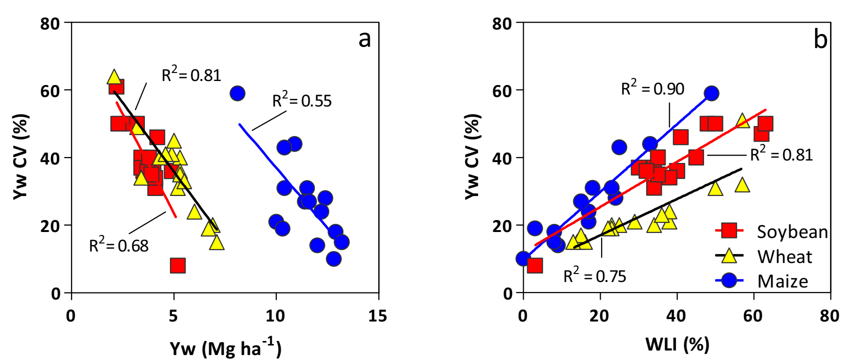

Fig. 5. Coefficient of variation (CV, in%) for water limited yield potentials (Yw), calculated for reference weather stations, as a function of (a) water-limited yield potential (Yw), and (b) water limitation index (WLI, *i.e.*, difference between yield potential and water-limited yield, expressed as percentage of yield potential), for soybean, wheat, and maize. Significant negative (a) and positive (b) correlations were found for the three crops ($P < 0.05$).

(both absolute residuals and relative to the Ya estimated for each year).

3. Results

3.1. Selected weather stations and crop area coverage

Harvested soybean and maize area averaged 17.2 and 3 Mha during the 2006–2012 period, respectively. Spatial distribution of soybean and maize area was remarkably similar, with highest crop area density in the central Pampas (Fig. 2). In contrast, wheat production area (4.5 Mha) was concentrated in the southern Pampas. A relatively small number of RWS buffers (16 for soybean and wheat, and 15 for maize) was sufficient to cover 53, 50 and 48% of national soybean, wheat and maize harvested area, respectively. Furthermore, the eight CZ where the selected RWS were located accounted for 81, 70 and 78% of total national crop area for soybean, wheat, and maize, respectively (Fig. 2). Five of these climate zones are located in the Pampas (CZ I– IV and VII), two in the Chaco region (CZ VI and VII), and one in the Espinal (CZ VIII) (Hall et al., 1992; Viglizzo et al., 2011b).

3.2. Variation in actual yields across Argentina

National average Ya calculated by the upscaling method was 2.7, 3.0, and 6.8 Mg ha^{-1} for soybean, wheat and maize, respectively (Table 1). These values were in agreement with the national Ya reported by the Argentine Agricultural Ministry for the three crops (*t*-test, $P > 0.45$), indicating the robustness of the method used to upscale results from RWS buffers to larger geographic areas (Fig. 3). There was a large variation in Ya across RWS buffers in Argentina as a result of the large spatial variation in climate, soils and cropping systems (Supplementary Table 3–5). For instance, maize Ya ranged from 3.2 to 8.9 Mg ha^{-1} across RWS (Supplementary Table 5). The highest maize and soybean Ya were observed in the central Pampas, while the highest wheat Ya was observed in the southeast Pampas.

3.3. Spatial and temporal variation in water-limited yield potential

National Yw was 3.9, 5.2, and 11.6 Mg ha^{-1} for soybean, wheat and maize, respectively (Table 1). Wheat Yw was highest in the southeast and decreased towards the northwest from 6.9 Mg ha^{-1} in CZ II to 2.1 Mg ha^{-1} in CZ V (Fig. 4b). Maize Yw was more stable across regions, ranging between 10.0 and 13.2 Mg ha^{-1}, except in CZ I (*i.e.*, southwest Pampas) where it barely exceeded 8.1 Mg ha^{-1} (Fig. 4c). The highest soybean Yw was found in the CZ VI (5.2 Mg ha^{-1}), which corresponds to the sub-humid Chaco region. However, Yw in CZ VI might have been overestimated since the RWS was located in the western edge of its crop area, where precipitation is higher. CZ VII, IV and III, in central and west Pampas, also presented high soybean Yw, of *ca.* 4.0 Mg ha^{-1} (Fig. 4a). Lowest soybean Yw was found in the southwest Pampas (2.2 Mg ha^{-1}), which is consistent with the results for maize. Second crop soybean Yw was consistently lower than single soybean crop Yw, with higher differences in the south (up to 30%) than in the northern climate zones (Supplementary Table 3). Likewise, soybean double crop showed higher year-to-year variation in Yw than single soybean crop (Supplementary Table 3).

For most RWS, low Yw was associated with high inter-annual variability in Yw and *vice versa* (Fig. 5a). Variation in water supply (soil water content at sowing plus in-season precipitation) across RWS explained the previous relationship, as indicated by the positive correlation between the coefficient of variation (CV) for Yw and the WLI (Fig. 5b). The WLI may also reflects differences in producer's preference to grow certain crops in best soils. For example, the WLI of soybean and maize in CZ I were different (61 versus 49%, respectively), which may be related to producer's choice to grow maize in the best soils (Supplementary Table 1).

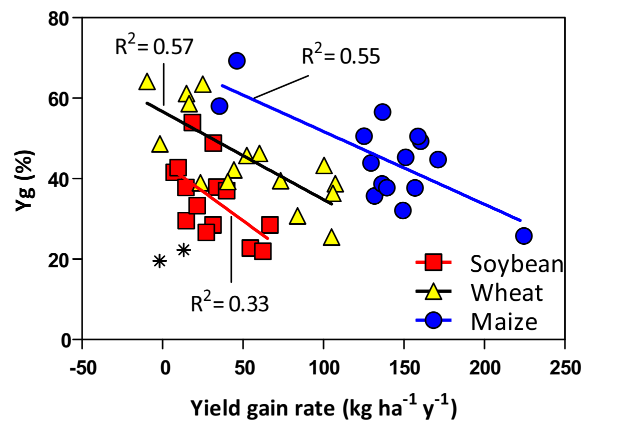

Fig. 6. Yield gaps (Yg, 2006–2012 average) at each reference weather station as a function of yield gain rate (kg ha^{-1} y^{-1}) from 1992 to 2012 for soybean, wheat and maize. Significant negative correlations were found for the three crops ($P < 0.05$). Soybean values for CZ I showed a different pattern of Yg because of a severe water limitation, and are indicated as *.

3.4. Spatial and temporal variation in yield gaps for soybean, wheat and maize in Argentina

Average Yg in Argentina was 1.3, 2.1, and 4.8 Mg ha^{-1} for soybean, wheat and maize, respectively (Table 1). Yg, expressed as percentage of Yw, was remarkably smaller for soybean (32%) than for wheat and maize (41%), and this difference was consistent across RWS (Fig. 4). Yg of the three crops varied widely within the country, ranging from 22 to 69% of the Yw across CZ. Despite such variability, there was no consistent correlation between Yg and Yw, Ya or yield CVs ($P > 0.45$). In general, largest gaps were found in areas that had been recently converted into annual crop production while smallest gaps were found in those areas with long agricultural history. The highest Yg (45 to 69% of Yw) were found in climate zones V and VI, which are located in the Chaco region (Fig. 4). Western climate zones (*i.e.*, VII and VIII) also exhibited large gaps, ranging from 40 to 60% of the Yw. Small Yg were found in central Pampas (*i.e.*, climate zones III and IV), reaching *ca.* 25% (for soybean) and between 30 and 40% (for maize and wheat) of the Yw. The southern CZ (*i.e.*, I and II) had intermediate Yg for maize and wheat (*ca.* 40% of Yw), but with a sharp longitudinal gradient, with decreasing Yw and increasing variability from east to west, due to a parallel decrease in rainfall together with an increasing frequency of soils where a caliche layer limits the rooting depth (Monzon et al., 2012). Interestingly, soybean crops in CZ I had the lowest Yw, with the highest inter-annual variability, but the lowest yield gap (Supplementary Table 3). There was a significant negative relationship ($P < 0.05$) between the size of the Yg and yield gain rates observed during the last 20 years analyzed (1992–2012), suggesting that technological improvement in crop practices have not homogenously reached and/or impacted the entire Argentine grain production area(Fig. 6).

Interestingly, magnitude of Yg at RWS, CZ, and national scales depended upon year (Fig. 7a). For the three crops, Ya approached Yw in dry years (*i.e.*, in years with a high WLI), while Yg was significantly higher in wet years (Fig. 7b). The contrasting pattern in wet *versus* dry years, which was consistent at all spatial levels, was in agreement with the finding that the lowest soybean Yg occurred in the most water-limited region (*i.e.*, CZ I, Fig. 4).

Table 1
Actual yields (Ya), water-limited yield potentials (Yw), yield gaps (Yg), and attainable crop production (ACP) for soybean, wheat and maize in Argentina based on 2011/12 crop area. Actual yields are 7-y (2005/06–2011/12) averages. See Section 2.4 for details on calculation of ACP.

	Ya (Mg ha^{-1})[a]	Yw (Mg ha^{-1})[a]	Yg (Mg ha^{-1})[b]	Crop area (Mha)	ACP (Mt)[a]
Soybean	2.65 (14%)	3.91 (18%)	1.26 (32%)	17.6	55 (18%)
Wheat	3.02 (23%)	5.16 (21%)	2.14 (41%)	4.5	19 (21%)
Maize	6.79 (18%)	11.60 (14%)	4.81 (41%)	3.7	34 (14%)

[a] Number between brackets shows the coefficient of variation (in%).
[b] Number between brackets shows Yg as a percentage of Yw.

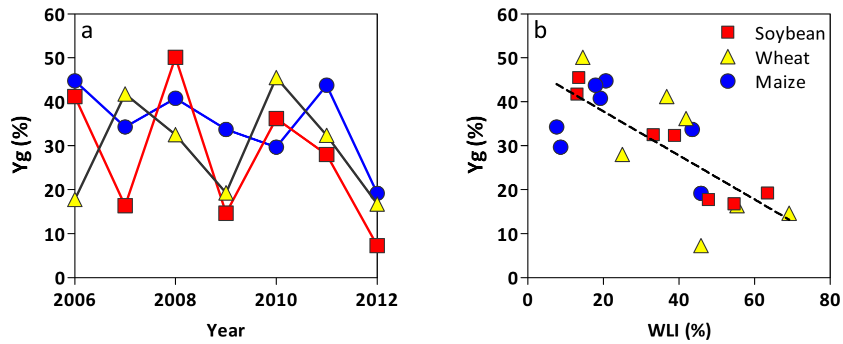

Fig. 7. Argentine yield gaps (Yg) for each cropping season (2006–2012), expressed as percentage of water-limited yields, for soybean, wheat and maize, as a function of: (a) harvest year and (b) water limitation index (WLI, *i.e.*, difference between yield potential and water-limited yield for each cropping season, expressed as percentage of yield potential). A significant negative correlation was found between Yg and WLI for the three crops ($P < 0.05$), with no significant differences in the linear regression parameters among crops ($P > 0.46$).

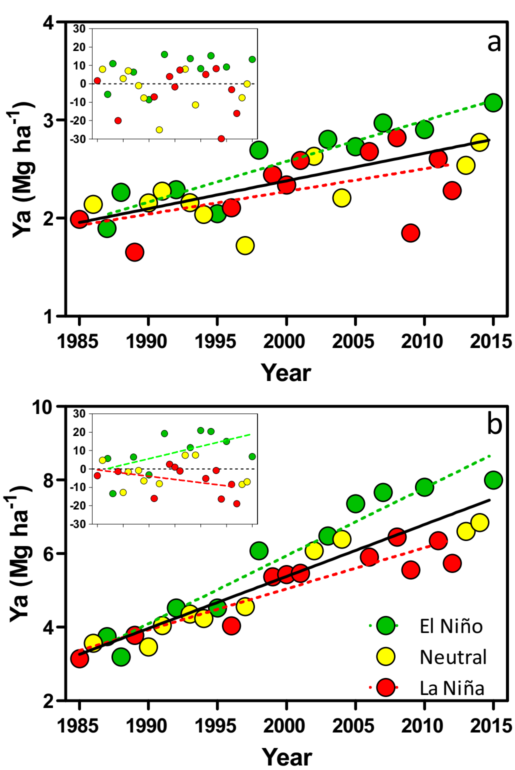

Fig. 8. Trends in actual yield (Ya) from 1985 to 2015 in Argentina as related to El Niño—Southern Oscillation phenomenon (ENSO) for soybean (a) and maize (b). The insets show the relative Ya residuals (%) obtained from the regression analysis between Ya and year. For maize, there was a significant difference between the slopes of the relative residuals of El Niño and La Niña phases over time ($P < 0.05$).

3.5. ENSO phenomenon effect on Argentine actual and attainable crop production

In relative terms, the effects of the ENSO phenomenon on soybean Ya was constant over time (Fig. 8a), while there was an increasingly higher difference in maize Ya between ENSO phases over time, both in absolute and relative terms (Fig. 8b). Wheat Ya was not affected by the ENSO phenomenon.

Yield gap closure to a level of 20% of Yw would lead Argentina to a production of 55, 19, and 34 Mt of soybean, wheat, and maize, respectively, without expansion in cropland area (Table 1). However, national Yw, and hence ACP varied significantly among years because of climate variability, with CV ranging from 14 to 21%. Inter-annual variation in summer crops ACP were partially explained by the influence of the ENSO phenomenon. During "La Niña" years, Argentine maize ACP was significantly lower and more variable than during "El Niño" and Neutral years ($P < 0.05$, Fig. 9). Likewise, soybean ACP was higher in "El Niño" years and lower in "La Niña" years ($P < 0.05$), with no significant variation in the inter-annual variability within each phase (Fig. 9). The ENSO phenomenon had a strong effect on summer crops Yw and crop production in a limited but highly productive region of Argentina (*i.e.*, CZ III and IV for soybean, and II and III for maize, Fig. 4). On the other hand, the ENSO phenomenon did not have a clear influence in wheat ACP ($P = 0.72$).

4. Discussion

Argentina is one of the major grain exporter countries since early 20th century. Assuming a standard nutritional unit of 500 kg grain equivalent per capita per year (Connor et al., 2011), Argentina produces enough grain to feed *ca.* 200 million people, that is, five times its current population. In addition, Argentina could have potentially produced an extra 7.4 Mt of soybean, 5.2 Mt of wheat and 9.2 Mt of maize on existing cropland area, by closing national average Yg calculated for the 2006–2012 period (32 to 41% of Yw depending upon crop) to an attainable level of 20% of Yw. If the extra crop production amount achieved through yield gap closure had been exported, which was very likely given the low internal demand, it would have represented an increase in soybean, wheat

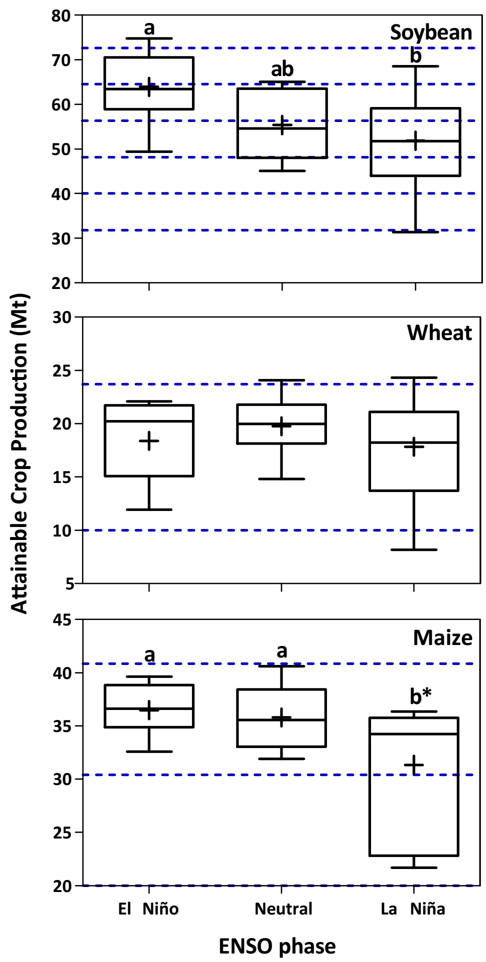

Fig. 9. Attainable soybean, wheat and maize production of Argentina as affected by "El Niño"—Southern Oscillation phenomenon (ENSO) based on 2011/12 crop area. Different letters, within the same panel, indicate significant differences among ENSO phases at $P < 0.05$ (Kruskal–Wallis test). Distance between horizontal dashed lines represents 10% of global exports for each crop (2006–2011 average, FAOSTAT 2015). Attainable maize production in La Niña years presented a significant higher variance (Levene's test, $P < 0.05$). See Section 2.4 for details on calculation of attainable crop production.

and maize global exports of a respective 9%, 4% and 9%.[2] In turn, this increase in global exports would have been sufficient to cover the food requirements of 44 million people. However, Argentine production and its contribution to global grain markets greatly varies due to climate variation as related to ENSO phenomenon (Podestá et al., 1999; Iizumi et al., 2014). Furthermore, the reported effects of the ENSO phases on Argentine maize production tended to be greater during the last cropping seasons (Fig. 8), despite increments of late-sown maize, which has lower Yp than early sowings, but with significant reductions in Yw CV (Maddonni, 2012; Mercau et al., 2014). This pattern might reflect that attainable yields are even more sensible to the ENSO phenomenon than Ya, and, as Ya approaches Yw, the former will become more variable, if crop management practices do not change. For example, in "La Niña" years there is a high probability of widespread droughts that may reduce Argentine maize production capacity by more than 30%, with a parallel 10% impact on global maize exports. Likewise, average attainable soybean production in "La Niña" years is 12 Mt lower than in "El Niño" years, which represents a reduction of global exports of soybean by 15% (Fig. 9).

In a global context, size of Yg of major Argentine cereal crops is moderate. Wheat and maize Yg in Argentina represented 41% of their respective Yw, which were similar to those estimated for sunflower by Hall et al. (2013), but considerably higher than the gaps reported for some major high-technology cereal-producing regions, *e.g.*,wheat in Germany and maize in Nebraska, USA, which had gaps of ∼20% (Grassini et al., 2011; Van Wart et al., 2013b). At the other extreme, Yg in Argentina were much smaller than those reported for smallholder production systems in Sub-Saharan Africa (Tittonell and Giller, 2013; Kassie et al., 2014). Considering an 'S-shaped curve' production function in response to inputs (De Wit, 1992), African smallholder agriculture are located at the low-input/low-response zone, and the high technology cereal-producing regions are at the high-input/plateau zone (Tittonell, 2013). Argentine cropping systems are between these two extremes, within the 'high-response zone', but with high variability among regions and farmers. This could partially explain the high rate of crop yield increase that Argentina had during the last twenty years. In fact, Argentina is one of the few countries exhibiting rates of yield increase that are sufficient to double current crop production by 2050, though this will only be achieved if current rates of yield gain are sustained over the next 35 years (Ray et al., 2013). Even with no changes in current Yw, if Argentina is able to sustain its current yield gain rates, the average national Ya will reach 80% of Yw by 2025, 2026 and 2038 for soybean, maize and wheat, respectively. Moreover, there is evidence that Yw and land productivity can be further increased in Argentina. For example, farmers are adopting concepts on zone management, climate forecasts (as related to ENSO), and in-season measurement (like soil water at sowing) to fine tune crop management (Bert et al., 2006; Monzon et al., 2007; Peralta et al., 2013), while land productivity can be increased by intensifying crop sequences in the Pampas (Monzon et al., 2014; J.F. Andrade et al., 2015).

Soybean Yg is considerably lower than Yg of maize and wheat in Argentina (32% versus 41% of Yw). This difference can be explained by: (i) higher vegetative and reproductive plasticity of soybean relative to maize (Andrade, 1995); (ii) Argentine soybean crops obtained *ca.* 60% of their N from biological N fixation (Collino et al., 2015), (iii) the requirement of P to reach 90% of the maximum yield for soybean is considerably lower than for wheat and maize (Hanway and Olson, 1980). Crops are typically nutrient-limited in Argentina, as the rates of fertilizers applied have increased but are still low relative to crop nutrient requirements (Calviño and Monzon, 2009; Lavado and Taboada, 2009), resulting in negative nutrient balances (Liu et al., 2010; MacDonald et al., 2011; Lassaletta et al., 2014). Considering that wheat, maize and sunflower Yg were remarkably similar, and 10% higher than soybean Yg, it is likely that these differences can be partly related to nitrogen deficiencies.

Argentina is not only an interesting case of study for its great potential for crop production and grain exports, but also for its great cropping system variability among regions which resulted in a wide range of Yw, Yg (Fig. 4) and year-to-year variation (Fig. 7). This variability had not been properly quantified in previous Yg assessments, mainly because these were global studies that did not account for spatial variation on soil and crop management within the country, or made no attempt to use yearly weather data, or were based on coarse weather, soil, and management data (Neumann et al., 2010; Licker et al., 2010; Foley et al., 2011; Mueller et al., 2012). For example, Neumann et al. (2010) roughly agreed with our national estimates of wheat and maize Yg, but such work was not sensitive enough to detect regional variations, whereas Licker et al. (2010) and Foley et al. (2011) grossly underestimated Argentine maize and soybean Yw. It has been suggested that Yg are

[2] Global exports were estimated from 2006 to 2011 averages (FAO, 2015).

higher when the risk associated to crop production is greater, *i.e.*, high coefficient of variation for yield (Fischer et al., 2009). Interestingly, despite the high variation in Yw, Ya and yield CVs found in Argentina, there was no correlation between any of these variables and the Yg. Other variables are likely to explain better the spatial variation on Yg, for example, crop history (*i.e.*, the number of years that a given region has been under commercial-scale agriculture) and technology level applied by farmers (Fig. 6). Indeed, we can distinguish contrasting scenarios for major agricultural regions of Argentina. In the Chaco region (*i.e.*, CZ V and VI), the Yg was largest probably because of the recent agriculture history and small yield gain rates observed during the last twenty years (1992–2012). Future efforts on research should be made to understand the socioeconomic factors that explain low yield gains in this region. At the central Pampas (*i.e.*, CZ III and IV), farmer's yields have significantly increased during the last 20 years and Yg tends to be lower than in the rest of the country. Since farmer's yield will reach the attainable yield in the medium-term, future on-farm yield increase in this region might rely on increases in Yw of individual crops or increasing crop intensity, or both.

The present study clearly shows that Yg varied significantly from year to year (Fig. 7). The temporal variation in Yg, which is an aspect that has not been analyzed in previous yield gap analyses, can bring some light on yield gap causes (Hall et al., 2013; Laborte et al., 2012; Van Rees et al., 2014; Van Wart et al., 2013b). Both Yw and Ya followed the same trend across years; however, Yw was more sensitive to wet years, relative to Ya, resulting in higher Yg in the more favorable wet years (Fig. 7b). In wet years, other non-water related factors became limiting, such as nutrient supply or incidence of insect, pests and pathogens, resulting in a large gap between Yw and Ya. In contrast, in dry years, water was the most limiting factor for crop production, and Yg was relatively smaller. Likewise, a combination of low summer rainfall and low soil water holding capacity were the major limiting factors for soybean yields in CZ I, hence, it was not surprising that soybean Yg was the lowest in this region (Fig. 4). The contrasting behavior of Yg in favorable *versus* non-favorable years might be related to farmer's risk aversion behavior and its impact on the level of applied inputs and technology. Specifically, since the level of applied inputs is likely to be determined based on the yield reached with normal or moderately adverse weather conditions, current management may have an unintended opportunity cost in favorable years with high Yw. Availability of ENSO-related climate forecasts and other early-season indicators (such as soil water content at sowing) can help to reduce the uncertainties associated with crop production, allowing farmers to take advantage of the favorable years and reduce the economic loses in adverse years (Bert et al., 2006).

5. Conclusions

Yield gap assessment performed in this study indicates that Argentina had the potential to substantially increase grain production of soybean, wheat and maize, by a respective 7.4, 5.2 and 9.2 Mt, without expanding cropland area. This potential grain surplus would have a great impact on grain global exports, but with significant variations across years because of the inter-annual climate variability related to the ENSO phenomenon. Magnitude of yield gap in Argentina depended upon year, with largest Yg in wet years and smallest Yg in dry years. Substantial variation in yield gaps was found across crop producing regions, which highlights the usefulness of the spatial framework applied in this study to target research and, ultimately, reduce gaps in areas where current yield is well below its potential.

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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.2015.10.001.

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Supplementary Table 1. Soil type, relative contribution to crop harvested area within reference weather station (RWS) buffer, and main soil characteristics. Note that different soil weights are given for maize, compared with wheat and soybean, since maize is typically grown in the best soils.

RWS	Soil types	Soil Weight (%)		Depth (m)	Topsoil texture	Subsoil texture	Slope (%)
		Maize	Wheat & soybean				
Azul	Typic Argiudol	50	40	1.8	Loam	Clay Loam	2
	Typic Argiudol	50	40	1.3	Clay loam	Clay	2
	Typic Natrudol	-	20	0.5	Clay loam	Clay	0
Balcarce	Typic Argiudol	50	35	1.8	Loam	Clay loam	2
	Typic Argiudol	50	35	1.3	Clay loam	Clay	2
	Petrocalcic Paleudol	-	30	0.8	Clay loam	Clay	2
Barrow	Typic Argiudol	50	-	1.8	Sandy clay loam	Clay	0
	Typic Argiudol	-	50	1.5	Loam	Clay loam	0
	Typic Argiudol	50	-	1.3	Loam	Clay loam	1
	Petrocalcic Paleudol	-	30	0.8	Clay loam	Clay	1
	Petrocalcic Paleudol	-	20	0.6	Sandy clay loam	Clay	1
Famaillá	Typic Haplustol	50	50	1.8	Loam	Sandy Loam	0
	Entic Hapludol	35	35	1.8	Sandy loam	Sandy Loam	0
	Aquic Ustiflivent	15	15	1.8	Silt loam	Sandy Loam	0
General Pico	Entic Hapludol	50	50	1.8	Sandy loam	Sandy loam	0
	Entic Haplustol	25	25	1.8	Sandy loam	Sandy loam	0
	Typic Ustipsament	25	25	1.8	Loamy sand	Loamy Sand	0
Gualeguaychú	Aquic Argiudol	50	50	1.8	Silty clay loam	Silty clay	0
	Argiudolic Peludert	30	30	1.8	Silty clay loam	Silty clay	3
	Argi-cromic Peludert	20	20	1.8	Silty clay	Silty clay	5
Laboulaye	Udortentic Haplustol	80	80	1.8	Sandy loam	Sandy loam	0
	Udic Haplustol	20	20	1.8	Loam	Sandy loam	0
Las Breñas	Udic Argiustol	40	30	1.8	Loam	Loam	0
	Ustic Ustocrept	60	40	1.8	Loam	Clay loam	0
	Typic Durostol	-	30	0.6	Loam	Loam	0
Marcos Juárez	Typic Argiudol	40	40	1.8	Silt loam	Silty clay loam	0
	Aquic Argiudol	30	30	1.8	Silt loam	Silt loam	0
	Udic Haplustol	30	30	1.8	Silt loam	Silty clay loam	0
Paraná	Aquic Argiudol	50	50	1.8	Silty clay loam	Silty clay	3
	Aquic Argiudol	25	25	1.2	Silty clay loam	Silty clay	3
	Typic Argiudol	25	25	1.8	Silt loam	Silty clay loam	0
Pehuajó	Entic Hapludol	45	45	1.8	Sandy loam	Sandy loam	0
	Entic Hapludol	40	40	1.8	Sandy loam	Sandy loam	0
	Thapto-argic Hapludol	15	15	1.8	Loam	Sandy clay loam	0
Pergamino	Typic Argiudol	35	35	1.8	Loam	Clay loam	0
	Vertic Argiudol	40	40	1.8	Silty clay loam	Clay	0
	Typic Argiudol	25	25	1.8	Silty loam	Silty clay loam	0
Pigüé	Typic Argiustol	-	35	0.6	Sandy clay loam	Clay	0
	Petrocalcic Paleudol	-	35	1.0	Loam	Clay loam	0
	Typic Haplustol	-	30	1.8	Loam	Loam	0
Pilar	Entic Haplustol	75	75	1.8	Silt loam	Silt loam	0
	Typic Haplustol	25	25	1.8	Silt loam	Silt loam	0
Rafaela	Typic Argiudol	35	35	1.8	Silt loam	Silty clay loam	0
	Aquic Argiudol	50	50	1.8	Silty clay loam	Silty clay loam	0
	Typic Argialbol	15	15	1.8	Silty clay loam	Silty clay loam	0
Río Cuarto	Entic Haplustol	45	45	1.8	Sandy loam	Loamy sand	0
	Typic Haplustol	15	15	1.8	Silt loam	Silt loam	0
	Typic Ustorhent	40	40	1.8	Loam	Loam	0

Supplementary Table 2. Soybean (single and double crop), wheat and maize management practices, as retrieved from local agronomists, applied to estimate water-limited and potential yields at each reference weather station (RWS).

RWS	Soybean						Maize			Wheat		
	Maturity group		Plant density (plant m^{-2})		Sowing date		Hybrid Maturity[a]	Plant density (plant m^{-2})	Sowing date	Cultivar maturity	Plant density (plant m^{-2})	Sowing date
	Single	Double	Single	Double	Single	Double						
Azul	IV	III	30	35	5-Nov	28-Dec	117	7	20-Oct	Inter-short	290	1-Jul
Balcarce	III	III	30	35	5-Nov	1-Jan	117	7	20-Oct	Inter-short	290	1-Jul
Barrow	IV	III	25	30	25-Nov	1-Jan	117	7	20-Oct	Inter-long	220	1-Jul
Famaillá	VIII	VIII	26	26	25-Dec	25-Dec	134	5.5	20-Dec	Inter-short	180	1-Jun
General Pico	IV	IV	25	30	5-Nov	10-Dec	124	6	20-Sep	Inter-long	270	20-Jun
Gualeguaychú	VI	VI	30	40	1-Nov	5-Dec	124	7.5	1-Sep	Inter-short	300	15-Jun
Laboulaye	IV	IV	28	36	25-Oct	5-Dec	124	7	5-Oct	Inter-long	220	1-Jun
Las Breñas	VIII	VIII	22	30	10-Dec	1-Jan	134	4.5	1-Jan	Inter-long	180	15-May
Marcos Juárez	IV	IV	28	30	25-Oct	5-Dec	124	7.2	25-Sep	Inter-long	250	1-Jun
Parana	VI	VI	30	40	15-Nov	5-Dec	124	7.5	25-Oct	Inter-short	350	20-Jun
Pehuajó	IV	IV	28	40	1-Nov	15-Dec	124	6.8	1-Oct	Inter-long	320	5-Jun
Pergamino	III	IV	32	35	1-Nov	10-Dec	124	7	25-Sep	Inter-long	240	1-Jun
Pigüé	III	-	20	-	20-Nov	-	-	-	-	Inter-long	200	15-Jun
Pilar	VI	VI	28	33	25-Nov	28-Nov	124	7	10-Dec	Inter-long	200	10-May
Rafaela	VI	IV	30	40	15-Nov	20-Dec	124	7.5	25-Oct	Inter-short	350	20-Jun
Río Cuarto	IV	IV	28	36	25-Oct	5-Dec	124	6.5	1-Dec	Inter-long	220	1-Jun

[a] Hybrid relative maturity rate as reported by argentine seed companies (Peterson and Hicks, 1973).

Supplementary Table 3. Yield potentials (Yp), water-limited yield potentials (Yw), actual yields (Ya) and yield gaps (Yg) for soybean for each cropping system (CS), reference weather station (RWS) and climate zone (CZ). The relative weights used to upscale the values from CS to RWS (CS Wt), from RWS to CZ (RWS Wt), and from CZ to the whole country (CZ Wt) are shown.

CZ	RWS	CS	CS Wt	CS Yp (Mg ha^{-1})[a]	CS Yw (Mg ha^{-1})[a]	RWS Wt	RWS Yp (Mg ha^{-1})[a]	RWS Yw (Mg ha^{-1})[a]	RWS Ya (Mg ha^{-1})	RWS Yg (Mg ha^{-1})[b]	CZ Wt	CZ Yp (Mg ha^{-1})	CZ Yw (Mg ha^{-1})[a]	CZ Ya (Mg ha^{-1})[a]	CZ Yg (Mg ha^{-1})[b]
I	Barrow	Single crop	0.80	5.5 (7%)	2.3 (60%)	0.60	5.2 (8%)	2.2 (61%)	1.7	0.5 (22%)	0.04	5.6 (8%)	2.2 (56%)	1.7	0.5 (22%)
		Double crop	0.20	4.0 (10%)	1.6 (79%)										
	Pigüé	Single crop	1.00	6.1 (8%)	2.3 (50%)	0.40	6.1 (8%)	2.3 (50%)	1.9	0.5 (22%)					
II	Azul	Single crop	0.70	6.3 (5%)	3.6 (38%)	0.29	5.8 (6%)	3.5 (36%)	2.0	1.4 (42%)	0.09	5.9 (6%)	3.4 (40%)	2.3	1.1 (33%)
		Double crop	0.30	4.6 (7%)	3.1 (40%)										
	Balcarce	Single crop	0.60	6.4 (6%)	3.1 (48%)	0.27	5.4 (9%)	2.8 (50%)	2.0	0.8 (30%)					
		Double crop	0.40	4.0 (12%)	2.4 (58%)										
	Pehuajó	Single crop	0.78	6.5 (4%)	3.9 (36%)	0.44	6.3 (4%)	3.7 (36%)	2.7	1.1 (29%)					
		Double crop	0.22	5.4 (5%)	3.2 (49%)										
III	Gualeguaychú	Single crop	0.80	6.5 (5%)	3.2 (50%)	0.10	6.3 (6%)	3.2 (50%)	2.3	0.9 (29%)	0.26	6.4 (5%)	4 (37%)	2.9	1 (26%)
		Double crop	0.20	5.6 (6%)	2.9 (53%)										
	Paraná	Single crop	0.77	6.2 (5%)	4.1 (37%)	0.30	6.0 (5%)	4.0 (37%)	2.7	1.3 (33%)					
		Double crop	0.23	5.6 (5%)	3.4 (46%)										
	Pergamino	Single crop	0.84	6.8 (5%)	4.3 (34%)	0.60	6.6 (5%)	4.1 (34%)	3.2	0.9 (22%)					
		Double crop	0.16	5.4 (6%)	3.2 (44%)										
IV	Marcos Juárez	Single crop	0.85	6.3 (4%)	4.2 (32%)	0.64	6.2 (4%)	4.1 (31%)	3.2	0.9 (23%)	0.24	6.1 (4%)	4 (34%)	3.1	1 (24%)
		Double crop	0.15	6.0 (4%)	3.7 (42%)										
	Rafaela	Single crop	0.79	6.2 (5%)	4.0 (41%)	0.36	5.9 (5%)	3.8 (40%)	2.8	1 (27%)					
		Double crop	0.21	4.9 (6%)	3.1 (40%)										
V	Las Breñas	Single crop	0.89	4.9 (6%)	3.4 (38%)	1.00	4.9 (6%)	3.4 (37%)	1.9	1.5 (43%)	0.04	4.9 (6%)	3.4 (37%)	1.9	1.5 (43%)
		Double crop	0.11	4.4 (7%)	3.3 (33%)										
VI	Famaillá	Single crop	0.43	5.4 (5%)	5.3 (5%)	1.00	5.4 (5%)	5.2 (8%)	2.7	2.5 (49%)	0.03	5.4 (5%)	5.2 (8%)	2.7	2.5 (49%)
		Double crop	0.57	5.4 (5%)	5.1 (13%)										
VII	Laboulaye	Single crop	0.86	7.4 (4%)	4.4 (45%)	0.37	7.1 (4%)	4.2 (46%)	2.7	1.6 (37%)	0.24	6.7 (5%)	4.2 (39%)	2.5	1.8 (42%)
		Double crop	0.14	5.7 (5%)	3.1 (55%)										
	Pilar	Single crop	0.84	5.9 (7%)	4.0 (34%)	0.40	5.9 (7%)	3.9 (35%)	2.4	1.5 (38%)					
		Double crop	0.16	5.8 (7%)	3.0 (52%)										
	Río Cuarto	Single crop	0.92	7.4 (4%)	5.1 (36%)	0.23	7.3 (4%)	4.9 (36%)	2.3	2.7 (54%)					
		Double crop	0.80	5.6 (6%)	3.6 (43%)										
VIII	General Pico	Single crop	0.76	6.4 (4%)	3.6 (39%)	1.00	6.2 (4%)	3.4 (40%)	2.1	1.3 (38%)	0.05	6.2 (4%)	3.4 (40%)	2.1	1.3 (38%)
		Double crop	0.24	5.5 (5%)	2.9 (51%)										

[a] Number between brackets shows the coefficient of variation (in %)

[b] Number between brackets shows the Yg as a percentage of Yw.

Supplementary Table 4. Yield potentials (Yp), water-limited yield potentials (Yw), actual yields (Ya) and yield gaps (Yg) for wheat at each reference weather station (RWS) and climate zone (CZ). The relative weights used to upscale the yield values from RWS to CZ (RWS Wt) and from CZ to the whole country (CZ Wt) are shown**.**

CZ	RWS	RWS Wt	RWS Yp (Mg ha^{-1})[a]	RWS Yw (Mg ha^{-1})[a]	RWS Ya (Mg ha^{-1})	RWS Yg (Mg ha^{-1})[b]	CZ Wt	CZ Yp (Mg ha^{-1})[a]	CZ Yw (Mg ha^{-1})[a]	CZ Ya (Mg ha^{-1})	CZ Yg (Mg ha^{-1})[b]
I	Barrow	0.68	8.0 (7%)	5.3 (40%)	3.1	2.2 (42%)	0.19	8.0 (7%)	5.2 (42%)	2.71	2.5 (48%)
	Pigüé	0.32	8.0 (7%)	5.0 (45%)	2.0	3.1 (61%)					
II	Azul	0.23	8.3 (9%)	7.1 (15%)	4.1	3.1 (43%)	0.17	8.1 (9%)	6.9 (18%)	4.10	2.8 (41%)
	Balcarce	0.63	8.2 (9%)	6.9 (20%)	4.2	2.7 (39%)					
	Pehuajó	0.14	7.7 (7%)	6.7 (19%)	3.6	3.1 (46%)					
III	Gualeguaychú	0.12	6.8 (10%)	5.2 (31%)	3.3	1.9 (36%)	0.20	6.9 (9%)	5.2 (36%)	3.71	1.5 (29%)
	Paraná	0.39	6.8 (10%)	4.9 (41%)	3.4	1.5 (31%)					
	Pergamino	0.49	7.0 (9%)	5.5 (33%)	4.1	1.4 (25%)					
IV	Marcos Juárez	0.56	6.9 (9%)	5.3 (35%)	3.2	2.1 (39%)	0.17	7.0 (9%)	4.9 (37%)	2.97	1.9 (39%)
	Rafaela	0.44	7.1 (9%)	4.3 (40%)	2.6	1.7 (39%)					
V	Las Breñas	1.00	4.8 (14%)	2.1 (64%)	1.1	1.0 (49%)	0.04	4.8 (14%)	2.1 (64%)	1.05	1.0 (49%)
VI	Famaillá	1.00	7.4 (8%)	3.2 (49%)	1.1	2.0 (64%)	0.03	7.4 (8%)	3.2 (49%)	1.15	2.0 (64%)
VII	Laboulaye	0.38	7.0 (9%)	5.3 (36%)	2.9	2.4 (46%)	0.16	6.9 (9%)	4.3 (36%)	2.35	1.9 (45%)
	Pilar	0.48	6.8 (10%)	3.4 (34%)	2.1	1.3 (39%)					
	Río Cuarto	0.14	7.1 (6%)	4.6 (41%)	1.9	2.7 (59%)					
VIII	General Pico	1.00	7.1 (8%)	6.0 (24%)	2.2	3.8 (63%)	0.04	7.1 (8%)	6.0 (24%)	2.21	3.8 (63%)

[a] Number between brackets shows the coefficient of variation

[b] Number between brackets shows the yield gap as a percentage of Yw.

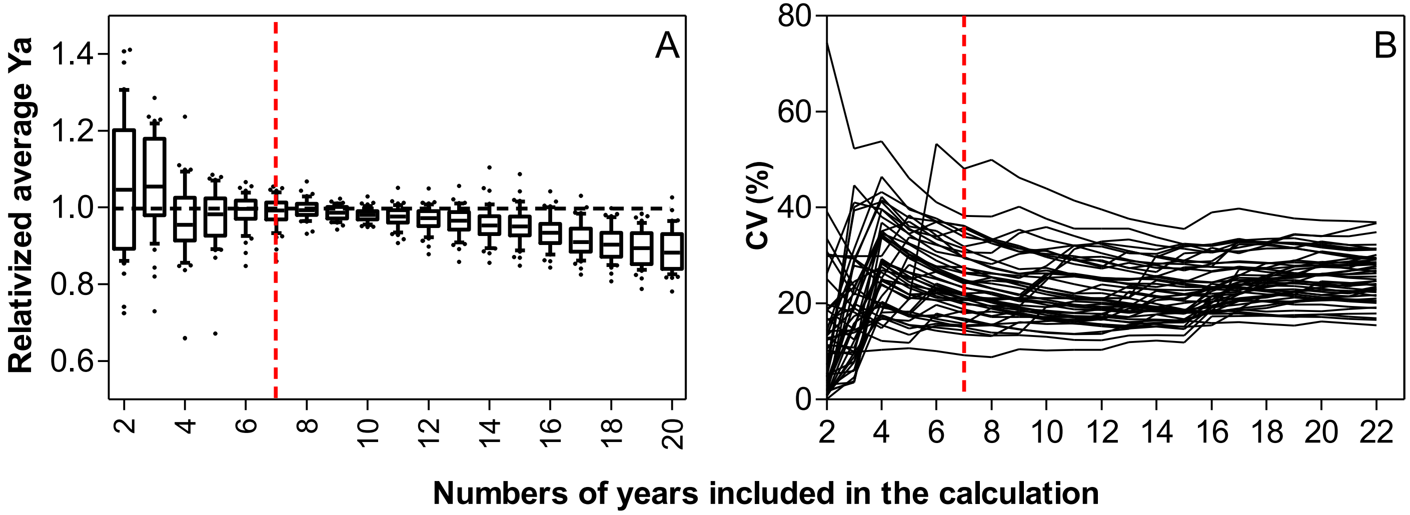
Supplementary Table 5. Yield potentials (Yp), water-limited yield potentials (Yw), actual yields (Ya) and yield gaps (Yg) for maize at each RWS buffer (RWS) and climate zone (CZ). The relative weights used to upscale the yield values from RWS to CZ (RWS Wt) and from CZ to the whole country (CZ Wt) are shown.

CZ	RWS	RWS Wt	RWS Yp (Mg ha^{-1})[a]	RWS Yw (Mg ha^{-1})[a]	RWS Ya (Mg ha^{-1})	RWS Yg (Mg ha^{-1})[b]	CZ Wt	CZ Yp (Mg ha^{-1})[a]	CZ Yw (Mg ha^{-1})[a]	CZ Ya (Mg ha^{-1})	CZ Yg (Mg ha^{-1})[b]
I	Barrow	1.00	15.9 (6%)	8.1 (59%)	5.2	2.9 (36%)	0.03	15.9 (6%)	8.1 (59%)	5.2	2.9 (36%)
II	Azul	0.23	16.4 (7%)	12.4 (28%)	6.3	6.1 (49%)	0.10	15.3 (7%)	12.0 (28%)	6.9	5.1 (42%)
	Balcarce	0.18	16.2 (6%)	10.9 (44%)	6.0	4.9 (45%)					
	Pehuajo	0.59	14.6 (7%)	12.2 (24%)	7.5	4.7 (39%)					
III	Gualeguaychú	0.10	13.5 (11%)	10.4 (31%)	5.1	5.2 (51%)	0.19	13.6 (9%)	11.4 (27%)	7.2	4.3 (37%)
	Paraná	0.30	13.5 (11%)	11.4 (27%)	6.4	5.0 (44%)					
	Pergamino	0.60	13.7 (8%)	11.6 (27%)	7.9	3.7 (32%)					
IV	Marcos Juárez	0.73	13.1 (11%)	12.0 (14%)	8.9	3.1 (26%)	0.23	13.3 (11%)	11.6 (22%)	8.2	3.3 (29%)
	Rafaela	0.27	13.8 (10%)	10.4 (43%)	6.5	3.9 (38%)					
V	Las Breñas	1.00	10.6 (16%)	10.3 (19%)	3.2	7.1 (69%)	0.04	10.6 (16%)	10.3 (19%)	3.2	7.1 (69%)
VI	Famaillá	1.00	12.9 (11%)	12.8 (10%)	5.6	7.3 (57%)	0.02	12.9 (11%)	12.8 (10%)	5.6	7.3 (57%)
VII	Laboulaye	0.40	14.1 (9%)	11.5 (31%)	7.2	4.3 (38%)	0.31	14.2 (8%)	12.4 (22%)	6.5	6.0 (48%)
	Pilar	0.32	14.1 (8%)	12.9 (18%)	6.4	6.5 (51%)					
	Río Cuarto	0.27	14.3 (7%)	13.2 (15%)	5.6	7.7 (58%)					
VIII	General Pico	1.00	12.1 (6%)	10.0 (21%)	5.5	4.5 (45%)	0.09	12.1 (6%)	10.0 (21%)	5.5	4.5 (45%)

[a] Number between brackets shows the coefficient of variation (in %)

[b] Number between brackets shows the yield gap as a percentage of Yw.

Supplementary Figure 1. (A) Average actual yields (Ya) for each department, starting from the most recent year (2012) and gradually incorporating more years back in time, relativized to the Ya estimated for each department for the year 2012 through linear regression (Ya as a function of year); and (B) their associated coefficient of variation (CV, %), as a function of the number of years included in the calculation. The vertical dashed lines indicate the most recent 7 years.



Supplementary Fig. 2. Observed daily incident solar radiation data, measured with radiometers at 6 locations across Argentina (OBS) plotted against daily solar radiation data retrieved from NASA-POWER (NASA). The red line represents y = x. The root mean square error (RMSE), and its components: squared bias (SB), squared difference between standard deviations (SDSD), and lack of correlation weighted by the standard deviation (LCS) are shown in inset.