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Potential for crop production increase in Argentina through closure of existing yield gaps

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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.