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Variability and limitations of maize production in Brazil: Potential yield, water-limited yield and yield gaps

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ABSTRACT

Occurrence of staple crops' yield gaps is object of study worldwide. A theoretical approach, model and statistical-based, was carried out to assess the climate-induced variability of rainfed maize yields and yield gaps in different regions in Central-Southern Brazil in both main growing seasons. A crop simulation model was used to estimate potential (Yp) and water-limited (Yw) yields through thirty crop seasons. Based on observed local farmers' averages and simulated yields, yield gaps related to water deficit (WYg) and crop management (MYg) were determined for first (sowing starting in September) and second (sowing starting in January) typical maize growing seasons. Overall higher average values of Yp and Yw (15.3 and 13.1 t ha^{-1}, respectively) were obtained in the first when compared to second growing season (10.3 and 9.2 t ha^{-1}, respectively). Statistical approaches pointed to similar importance between water and temperature on local biophysical limits in the scenarios. Assessed regions showed greater gaps due to crop management, with absolute averages of 5.7 and 3.2 t ha^{-1} in the first and second growing seasons, than gaps due to water deficit, with 2.1 and 1.2 t ha^{-1} in the first and second growing seasons, respectively. Opportunities for increasing average yields by closing the gaps were found to be predominantly through crop management improvements, in higher and more variable absolute levels on first than on second growing season. However, this management must be aligned with local climate, since its variability can determine relatively large gaps, even at intensively managed cropping systems. This study was able to highlight the importance of combining management, climatic and regional characteristics to provide a full perspective on main constraints of maize production increases.

1. Introduction

Maize is a major crop for Brazil (CONAB, 2016), where two main growing seasons are usual practice. First season, also known as the main season, is associated with the rainy period of Central-Southern Brazil, ranging from mid September – March (which also includes summer season). Second season (sown between Jan - Mar) have more restrictive climate conditions for crop growth; however it has experienced continuous increase (both in area and yield) when cultivated in succession to soybean as the main season crop in the major grain-producing regions (CONAB, 2016). At Southernmost (i.e., coldest regions of the country such as Rio Grande do Sul and parts of Paraná states) maize is predominantly produced in the first season; as latitude increases and climate becomes warmer, the crop can also be cultivated in the second season, which is currently a predominant condition in Midwestern Brazil. The territorial extension of the country determines a variety of environmental conditions that combined with crop management result in variable profiles of production systems. National maize average yields are 4.9 t ha^{-1} for first growing season and 5.7 t ha^{-1} for the second one (CONAB, 2016), indicating conditions for yield improvements. Maize yields lower than potential in South America are usually associated with use of unsuitable genotypes for the region and water and nitrogen deficiencies, indicating the importance of assessing such inputs when intensifying crop yields. Intensification of management is then the main way to increase yields, but the biophysical limits imposed by the environment and genetic material are usually unclear (Lobell et al., 2009) making crop management more difficult and prone to lower profits.

Crop yield increases are associated with the interaction between environment (climate and soil) and management, such as genetic material, plant population, nutrition, and plant protection. By knowing some of these characteristics, biophysical limits of yields, expressed by

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potential and water limited yields (Lobell et al., 2009), can be assessed. The maximum achievable yield – the potential yield concept (Yp) – is determined by the interaction between a given genotype and its plant population with solar radiation, air temperature and photoperiod, all under optimum crop management (no biotic and other abiotic limitation, such as crop nutrition, included). The maximum achievable yields under rainfed conditions – the water limited yield concept (Yw) is similar to Yp, but considering the water deficit as a limiting factor for a rainfed crop. These can be considered as reference levels since actual management conditions, affected by fertilization, pests, diseases and weed control, are not considered for their determination. Thus, a common way for determining Yp and Yw for a given crop is by using calibrated crop simulation models (Affholder et al., 2013; Grassini et al., 2015; Kassie et al., 2014; Lobell et al., 2009) based on a minimum input database of climate, soil and management practices; other approaches such as farmers' yield contest and best experimental yields can also be used (Lobell et al., 2009). By comparing simulated and observed yield levels, yield gaps can be determined as the difference from reference yields (Yp, Yw) and actual yields (Ya), therefore indicating the differences between potential levels and usual practice (Lobell et al., 2009). Since yield levels and yield gaps are strongly driven by climatic elements, these vary spatially and temporally. In Brazil, this kind of information is of particular interest due to wide territorial extension of the country and the cultivation of two maize growing seasons in many regions, which contribute to a great variety of production systems characteristics.

Increase of crop yields is also a matter of food security and achievement of sustainable goals such as preference for increases in productivity rather than increases in cultivated area (Foley et al., 2011). However, a critical first step for yield increases is the assessment of local biophysical yield limits and gaps as a way of strategically planning crop management towards highest achievable levels (Lobell et al., 2009). Further, besides understanding local biophysical limits, management towards increasing yields and closing the gaps will have to include alternative high-yielding practices as a manner to avoid and overcome possible environmental and social issues, such as the impacts originated from agricultural intensification (e.g., soil erosion, ground and surface water salinization, high levels of chemical input), loss of biodiversity and impacts on social communities (Licker et al., 2010), as also economic constraints (Mueller et al., 2012).

Whereas there is still a shortage of national and regional yield gap assessments in Brazil, especially comparing important crop producing regions, this study was developed with the main objective of assessing maize yield gaps and their main causes in typical rainfed production systems in six Brazilian regions considering their first and second growing seasons. Specific objectives of this study were: (i) to assess local biophysical limits of maize yields (potential and water-limited) and (ii) to assess regional and inter-annual variability of farmers' averages, biophysical limits and yield gaps of maize yields related to predominant climate and management conditions.

2. Material and methods

2.1. Assessed regions

The present study refers to municipalities as the assessed regions, which are located in two main political-divided regions in Brazil (Southern and Midwestern). Three regions are located in Southern Brazil (Passo Fundo, in Rio Grande do Sul state: 28°15′S, 52°24′W, RSPF; Guarapuava and Palotina, both in Paraná state: 25°23′S, 51°27′W, PRGU, and 24°16′S, 53°20′W, PRPA, respectively) and three regions are located in Midwestern Brazil (Maracaju, in Mato Grosso do Sul state: 21°37′S, 55°10′W, MSMJ; Diamantino, in Mato Grosso state: 14°24′S, 56°25′W, MTDI; and Jataí in Goiás state: 17°52′S, 51°41′W, GOJA). Assessed regions vary in size and in maize production, e.g., by means of their growing seasons characteristics (see Fig. 1 and Table 1).

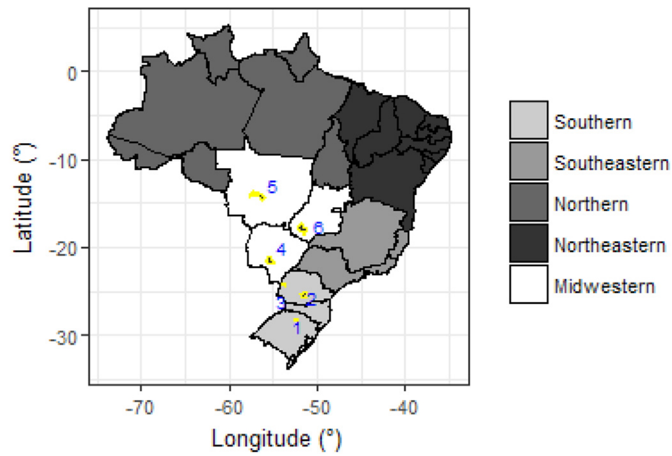

Fig. 1. Localization of the assessed regions in Brazilian territory. States are, according to numbers of assessed regions, respectively: 1 – Rio Grande do Sul; 2,3 – Paraná; 4 – Mato Grosso do Sul; 5 – Mato Grosso and 6 – Goiás. Total municipality area, are: 1 = 78 10^3; 2 = 317 10^3; 3 = 65 10^3; 4 = 529 10^3; 5 = 823 10^3 and 6 = 717 10^3 ha, respectively. Share of total area dedicated to cultivation of first and second growing seasons of the crop, respectively, are of: 1 = 86%; 2 = 10%; 3 = 3 and 61%; 4 = 1 and 33%; 5 = 1 and 10% and 6 = 3 and 22% (IBGE, 2015).

Southernmost regions (RSPF and PRGU) present only first growing season. The remaining regions present both growing seasons, wherein second growing season has shown prominence and greater importance over first season in the past years, mainly due to soybean cultivation on the main season. The scale of the present analysis ensured the use of historical crop yield and management data combined with environmental characterization, all representing average conditions for the region. The approach is flexible and can be adapted to local or broader demand by adjustment of available information and desired level of analysis.

2.2. Crop model and input data

The maize crop simulation model CSM CERES MAIZE, part of DSSAT system (DSSAT v. 4.6.0.18) (Jones et al., 2003), a process-based crop model used for estimating processes related to soil-plant-atmosphere and management interactions, was used for simulating maize yields under regional environmental and management conditions. DSSAT has a well established maize model and has been used with success around the world, as well as under Brazilian conditions (Battisti et al., 2017; Soler et al., 2007).

Historical weather data, daily maximum and minimum air temperature and sunshine hours, from 1983 to 2013 (National Institute of Meteorology - INMET, 2014) were used as input to the crop model. Daily solar radiation was obtained using Angströn-Prescott model, with "a" and "b" coefficients (Glover and McCulloch, 1958): a = 0.29 * cos latitude and b = 0.52, when sunshine hours were available, or by Bristow and Campbell model (Bristow and Campbell, 1984), when only temperature data were available. Daily rainfall data for all regions were retrieved from the National Water Agency (ANA, 2014) database for the same period. Reference evapotranspiration was estimated through Priestley-Taylor method, which is the standard method of DSSAT.

Soil texture and other physicochemical characteristics (bulk density, organic carbon and acidity in water) were used to characterize the average conditions of a predominant soil profile from each region (Table 1) (EMBRAPA, 2006; FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012). All predominant soil types from the assessed regions are nationally classified as Latossolos, known for their weathered nature (expressive content of iron oxides and hydroxides), as also being usually very deep, acid and well drained. These soils occur widely in tropical regions, but