University of São Paulo
“Luiz de Queiroz” College of Agriculture

How much irrigation would increase maize production in Brazil? - a crop modeling approach

Luís Alberto Silva Antolin

Thesis presented to obtain the degree of Doctor in Science. Area: Agricultural Systems Engineering

Piracicaba
2022

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versão revisada de acordo com a Resolução CoPGr 6018 de 2011

Advisor:
Prof. Dr. **FÁBIO RICARDO MARIN**

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RESUMO

Quanto a irrigação irá incrementar a produção de milho no Brasil? – uma abordagem através da modelagem de culturas

Reconhecida como uma das principais culturas de grande importância social e econômica para a maioria das comunidades humanas ao redor do planeta, a produção sustentável da cultura do milho (*Zea mays*), (ou seja, sem esgotar perigosamente os recursos naturais agrícolas), é vista de forma preocupante em um possível futuro onde a população mundial ultrapassará 9 bilhões de pessoas até 2050. Diante desse cenário, o Brasil se destaca tanto pelo seu grande potencial de expansão da agricultura quanto por estar entre as maiores áreas de cultivo de milho do mundo. Além disso, iniciativas como o Global Yield Gap Atlas (GYGA) realizaram estudos em mais de 50 países, avaliando o quanto a produtividade dos cultivos agrícolas poderiam aumentar sem ocupar novas áreas e usar com eficiência os recursos disponíveis. Dentro do escopo do projeto GYGA, este estudo visa avaliar a atual lacuna de produtividade da cultura do milho no Brasil e, adicionalmente, entender se a irrigação ajudará significativamente a fechar essa lacuna. Experimentos de campo foram realizados em pelo menos 3 regiões produtoras de milho do Brasil, com controle rigoroso de adubação, pragas, plantas daninhas e doenças, a fim de obter dados para calibrar um modelo de cultura e fornecer informações confiáveis sobre todo o potencial de produção em diferentes ambientes. Para definir quais locais representarão todo o potencial de produção (Yp) do país através de simulações, foi seguido o protocolo descrito pelo projeto GYGA para definir estações meteorológicas que representam diferentes Zonas Climáticas Homogêneas (CZ) e as áreas de que são abrangidas por estas estações. Além disso, um protocolo adicional foi adaptado para determinar um conjunto diferente de locais que foram utilizados para realizar um estudo do aumento da capacidade produtiva do milho através da irrigação. As estimativas mostram que, em média, as produtividades reais de milho (Ya) no Brasil estão 55,4% abaixo do Yp, embora um aumento na produção agrícola na mesma quantidade possa ser alcançado irrigando 50% das áreas de cultivo atuais. Estimativas do governo apontam que as áreas irrigadas irão crescer em cerca de 30% até 2030, o que fará com que a produção de milho mal supere os valores atuais. Nossos resultados mostraram que é possível aumentar os níveis de irrigação para atingir todo o potencial das culturas de milho sem comprometer os recursos hídricos disponíveis. No entanto, ainda são necessários esforços do poder público para maximizar a utilização eficiente dos recursos hídricos pelas lavouras, como investimentos em programas científicos de adaptação genética à seca e assistência social para auxiliar os agricultores na implantação de áreas irrigadas de forma sustentável. O trade-off entre aumentar a produção e expandir as áreas irrigadas, deve ser planejado para não afetar regiões pobres onde a escassez de água já limita a potencialidade da agricultura e ser focado em locais onde os recursos estão totalmente disponíveis para fechar a atual lacuna de produção de milho no Brasil. Os resultados deste estudo devem fornecer dados confiáveis para tomadores de decisão e na construção de novas políticas públicas, como no planejamento de programas governamentais que visam a expansão de áreas irrigadas.

Palavras-chave: *Zea mays*, Modelagem de culturas, Produtividade potencial, Irrigação

ABSTRACT

How much irrigation would increase maize production in Brazil? – a crop modelling approach

Acknowledged as one of the main crops with a major social and economic importance for most human communities worldwide, maize (*Zea mays*) production sustainability, i.e., without dangerously depleting agricultural natural resources, is evaluated as concern in a foreseen future where world population will surpass 9 billion people by 2050. In face of such scenarios, Brazil stands itself both by the higher potential of agriculture expansion and also to be amongst the largest maize cropland areas on Earth. Additionally, initiatives such as the Global Yield Gap Atlas (GYGA) have conducted studies in more than 50 countries, evaluating how much crop production yields could increase without occupying new areas and efficiently using the available resources. Within the scope of the GYGA project, this study aims to evaluate the current yield gap of maize production in Brazil, and additionally understand whether irrigation will significantly help on closing this gap. Several field experiments were caried in at least 3 maize producing regions of Brazil, with rigorous control of fertilization, pest, weed and diseases, in order to obtain data to calibrate a crop model and deliver reliable information about the full potential of production across different environments. For defining which locations will represent the whole country yield potential (Yp) through simulations, was followed the protocol described by the GYGA project to define weather stations that represent different Homogeneous Climate Zones (CZ) and the buffer areas that are covered. Moreover, an additional protocol was followed in order to determine a different set of locations that can be used to carry irrigation studies for increasing maize production. Estimates has shown that in average, actual maize yields (Ya) in Brazil are 55.4% below the Yp, although an increase on crop production by the same amount could be reached by irrigating 50% of current cropland areas. Government estimations has pointed that irrigated areas will be increased by near 30% of the areas that are cropped nowadays, which will aid the maize production to barely surpass current values. Our findings showed that it is possible to increase irrigation levels in order to reach full potential of maize crops without compromising the available water resources. However, is still required public efforts to maximize the efficient utilization of water resources by crops, such as investments on scientific programs of genetic adaptation for drought and social assistance to aid farmers on implementing irrigated areas in a sustainable way. The trade-off between increasing production and expanding irrigated areas, must planned to do not affect poor regions where water scarcity already limits the potentiality of agriculture and be focused on locations where resources are fully available to close the current gap of maize production in Brazil. Results from this study should provide reliable data for decision-makers and new public policies, as such governmental programs aiming to plan the expansion of irrigated areas.

Keywords: *Zea mays*, Crop modelling, Yield potential, Irrigation

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1. INTRODUCTION

Agriculture has as a primary objective to provide at least 50 nutrients, on which human existence would not be possible in its current state. Adequate supply of these nutrients are essential attributes for building productive and healthy societies. The world has experienced, in recent decades, noticeable increases in food supply and a decrease in the scarcity of carbohydrates and proteins (Evenson and Gollin, 2003a). Such increases were mainly due to the development of high-yield agricultural cultivars, where the expansion of our food supply allowed humanity to achieve a greater caloric intake and reduce child malnutrition (Evenson and Gollin, 2003b).

It is expected that the world population will increase between two to three billion people by 2050 (Foley et al., 2011; Godfray et al., 2010) and income increase will impact aspects related to consumption choices. In addition, it is estimated that developing countries will concentrate the highest increases in per capita income, where the consumption of calories and proteins, mainly from animal origin (FAO, 2016), has still a great potential for growth. To face such challenges, projections indicate that agricultural production is required to be increased up to 60% by 2050 (Alexandratos and Bruinsma, 2012; Lobell et al., 2009).Still, the world meat demand is expected to increase by c.a. 100% (Godfray et al., 2018) in 2050, which raises concerns on grain supplies for livestock feeding; maize (*Zea mays*) in one of the main inputs for the feedstocks (Salami et al., 2019). Thus, maize is a key-crop for future world food security scenarios (Tanumihardjo et al., 2020), having Brazil as the third-largest world maize producer and responsible for a relevant share of world exportations (FAO, 2021) and thus playing a key role for global food security. Considering the rise in world future food demand, there is still little room for cropland area expansion in Brazil and around the world (Phalan et al., 2013; Strassburg et al., 2014; Vieira Filho, 2016). The Midwest is the main producing maize region in Brazil, in which cropping systems are basically constituted of soybean during the summer season (also called “in season maize” or “safra”), followed by off-season maize (“safrinha”) where 73% of the national production is harvested in 13 million hectares (CONAB, 2021).

A few decades ago, little was discussed about the need to increase agricultural productivity on a global scale. On the contrary, simulations with general equilibrium computer models projected the maintenance or even the fall of agricultural prices (Van Ittersum et al., 2013). Currently, there is a notable change in this perception. An apparent consensus is perceived that the maintenance of the current agricultural model can lead to a dramatic increase in food prices, poverty and hunger in the world. In this sense, Marin et al. (2016) suggests the intensification of agriculture as a pressing need for this scenario not to be confirmed.

According to USDA (2018), Brazil is currently the third largest maize producer in the world, with a total of approximately 96 million metric tons, of which about 50 million tons are destined for animal consumption (ABIMILHO, 2018) which points this commodity as one of the main constituents of all plant-based protein produced worldwide. Recent studies, however, indicated that it is still possible to increase production within the area currently available. For a tropical environment in which Brazilian maize is cultivated, there are still few studies that follows an approach involving experimentation for potential conditions and accompanied by simulations using properly calibrated mechanistic models (Affholder et al., 2013; Andrea et al., 2018). Additionally, such initiatives can lead to the identification of production areas aimed to reduce productivity gaps for crops in general.

The majority of maize the production in Brazil is concentrated at the off-season and this explains high yield variability in comparison with summer crops, mainly due water shortage towards the end of the crop cycle (Andrea et al., 2018; Gouesnard et al., 2002; Llano and Vargas, 2016). Supplementary water by irrigation is thus supposed to be a potential solution for compensating losses related to water stress (Panda et al., 2004). Previous efforts have identified the meaningful impact of irrigation on off-season maize production, as an alternative to reduce yield gaps. Nóia et al. (2020), pointed an increase on yields around 60%, considering the suitability for expanding irrigated areas in Brazil. Battisti et al. (2020) has shown that some regions in Midwest Brazil are reaching low levels of production due scarce water availability during reproductive phase for off-season maize (Nóia Júnior and Sentelhas, 2019). Thus, a viable solution would be supplementary irrigation during key-crop development stages. A crop modelling approach was evaluated by Soler et al. (2007), where they found that yield depletion caused by late sowing dates is around 21% in irrigated off-season maize crops when compared with rainfed systems (55%). Still, considering the foreseen climate change, Martins et al. (2019) estimated losses in production below 20% for irrigated areas with longer cycle length cultivars, and increases reaching gains of 20% for areas more suitable to expand irrigation, for producing regions of Northeast Brazil. In spite of the complexity in which the mentioned studies have shown on describing the benefits of irrigation for off-season maize crops, they are still missing an overall approach that accounts the suitability of water resources available for such purposes and how it would expand Brazilian production.

Conceptually, the difference between actual yields (Ya), observed under operating conditions, and potential yields (Yp) (or achievable yields limited only by water deficit-Yw) is a robust quantitative indicator that has been used in such analysis (Lobell et al., 2009). The application of the concept of agricultural production efficiency for maize in Brazil can provide a basis for strategic analysis on cost trends and future prices of grain, oil and bran, including the demand and cost for new areas, in addition to competition with other activities related to the ground utilization.

Initiatives such as the Global Yield Gap Atlas (GYGA, www.yieldgap.org, Van Ittersum et al., 2013) have already produced reliable data sustained under rigorous protocols (Grassini et al., 2017; van Bussel et al., 2015) that can be used to identify the production potentiality in Brazilian maize crops. However, there is still room for evaluating the potential effect of irrigation on off-season maize yields, as well as to verify in which producing regions irrigation could be expanded considering the water availability in natural sources.

The average yield of maize crops in Brazil is currently around 5.5 t ha^{-1}, which is far behind numbers achieved at farm contests, where production amounts exceed 13.5 t ha^{-1} (Syngenta, 2017). This reveals that the maize cultivation in Brazil has potential yet to be explored, thus still being able to bring greater profitability to producers and ensure world food security. However, considering the results of recently published studies in temperate zones (Grassini et al., 2015b, 2015a; La Menza et al., 2017; Merlos et al., 2015), the hypothesis arises that even the high levels of yields reported (ABIMILHO, 2018; CONAB, 2022; Syngenta, 2017)may still fall short of the crop's yield potential. Nevertheless, if this hypothesis is correct, perhaps the current level of production efficiency (or yield-gap) of Brazilian producers under different water regimes are not well known.

One of the greatest contributions that scientific research can provide to the intensification of the maize production system in Brazil is the identification of regions that have the potential for increase production under sustainable conditions, considering better soil and climate conditions and thus allowing the following gains: (i) the analysis of the efficiency of agricultural production provides subsidies to identify the main factors (genetics, soil, water and plant management) that limits crop productivity; (ii) by allowing prioritization of resources for research, development and intervention and (iii) the results of this type of analysis are input data for general and partial economic equilibrium models, tools used for future projections of food security that involve the use of land, assessment of the impact of climate change and future agricultural scenarios on crops and land use.

A few other studies were carried out to quantify the productive efficiency of the Brazilian maize crops (Argenta et al., 2003; Cardoso et al., 2004; De Assis et al., 2006a, 2006b), but these studies were not based on an robust protocol for generating reliable results and for spatial extrapolation at local, regional and national scales, in addition to not having the necessary consistency in terms of methods and data sources, which makes complicate to perform comparisons with other studies. To our knowledge, it is not yet available for Brazil a robust analysis on the productive efficiency of maize in a tropical environment, following a consistent methodology and comparable to what has been done in the rest of the world, which predominantly follows the protocols developed by the GYGA project. Thus, this study follows the detailed examination through planned and properly conducted experiments to reach the potential yield of the crop (in at least two Brazilian maize producing regions) and to calibrate simulation models for this reality, to use the GYGA protocols with objective of developing an atlas of potential maize production in Brazil (at a local, regional and national scale), thus enabling a database for the subsequent identification of limiting and restrictive factors for the crop and the areas that should be prioritized to raise yield efficiency.

As future projections are pointing towards a scenario of water limitation, one of the main concerns in this study is to address and analyze the water productivity of maize crops across different producing regions, since current biophysical crop models are able to deal with the processes related to water consumption in a very robust way (Jones et al., 1986). As known, water productivity is given by the ratio between agricultural yield and crop water consumption, i.e., the amount of grain produced per volume of water lost by evapotranspiration (Passioura and Angus, 2010). This approach has already been validated for some crops such as maize (Grassini et al., 2011a), wheat (Passioura and Angus, 2010; Patrignani et al., 2014), sunflower (Grassini et al., 2009) and soybean for the Corn Belt region in US (Grassini et al., 2015a). Understanding this relation will help to comprehend and compare the role of maize crops in the dispute for water resources in the different producing regions of Brazil and it has not yet been determined in an organized and exhaustive way.

2. OBJECTIVES

2.1. General objectives

Fulfill the knowledge gap on how much water irrigation would increase maize crop yields and what Brazilian regions could meet crop water demand, in order to substantially close production gaps and bring yields closer to their full potential.

2.2. Specific objectives

i. Quantify and analyze the crop yield potential for maize in at least two producing regions of Brazil, based on field experiments and protocols adapted to tropical conditions;

ii. To produce a national map based on international protocols, that presents the production efficiency of Brazilian maize across the main producing regions;

iii. Estimate the possible area expansion of the irrigated off-season maize in Brazil considering the water availability in natural reservoirs in Brazil;

iv. Estimate how much irrigation would increase the maize yield across Brazilian producing regions.

3. HIPOTHESYS

i. It is possible, sustained on scientifically accurate protocols, to estimate biophysical process of maize crops in several producing regions of Brazil, by using well calibrated crop models, i.e., based on datasets generated on rigorous field experiments at different producing regions;

ii. The production efficiency and the potential of expansion of maize crops without the increment of cropland area, through an exhaustive assessment of sustainable water resources management, are still unknown;

4. LITERATURE REVIEW

4.1. Economic and social prospects of maize crops

Maize crops are considered one the most important human cultivated plants worldwide, explained by the key nutritional value and agricultural role well recognized by many farmers across the globe (Ricachenevsky et al., 2019). According to Wijewardana et al. (2016), maize withstands as the third most produced crop in the world, expecting an increasing demand of 45% in the first quarter of the 21st century. In Brazil, maize crops appears as the second largest grain production, only behind soybeans grain volume (USDA, 2018b).

It is important to mention, that human and livestock feeding are seen as the main focus of maize production. However, it is also very present as raw material for several industrial components, mainly in the subject of bioenergy resources (Choudhary et al., 2020; Eckert et al., 2018). In addition, corn grains are considered low-cost food resources, having a major role in the general society due the presence both on large croplands and poor communities (Galvão et al., 2014; Xavier et al., 2014).

Brazilian maize production, in 2020/21, is mainly distributed among the states of Mato Grosso (38%), Paraná (11%), Mato Grosso do Sul (7%), Goiás (10%), Minas Gerais (8%), Rio Grande do Sul (5%) and Bahia (3%) (CONAB, 2022). Those states are responsible for a producing 96 million tons of grains during 2020/21 season, reaching 83.8% of national maize grain volume. Forecasts of the Brazilian Ministry of Agriculture, by mid-2020’s, expected exports will be around 51,3 million tons when maize cropland areas will cover, approximately, 15.6 million hectares (MAPA, 2018).

Maize production in Brazil is mainly characterized by two seasons of crop farming, identified as “safra” or “(first)in-season” (“summer”) and the “safrinha” or “second-season” (“off-season”). Estimates of maize production are pointing a production of million tons in the “summer” season and million tons until the end of the “off-season” (CONAB, 2022). Currently, mostly of the Brazilian maize production is concentrated at the “off-season”, where almost 70% of the total grain volume is obtained. Although, for 2021/22 season, is expected a share increase up to 76% of national production.

4.2. Water as a booster factor for maize production

The types of vegetation identified in a certain region, can be described by the water flux present in the soil-plant-atmosphere system and how plants relate with environmental stresses found in the spatial-temporal variation (Dubbert and Werner, 2019; Miguez-Macho and Fan, 2021; Stephenson, 1990). As such for crops, hydrical conditions can directly affect several physiological processes (Bergamaschi and Matzenauer, 2014; Sans and Guimaraes, 2006).

Annual crops cultivated in warm environments, such as maize, are usually impacted with droughts, bringing several limitations that occurs alongside heat stresses that are very common within tropical and subtropical regions (Bergamaschi et al., 2010). Hence, crop yield potential can be limited due the inefficiency of water supply necessary to outcome stress limitations (Grassini et al., 2009).

A standard point for modern agriculture refers that crops with higher yield potential level have their full capacity limited mainly by water (De Ponti et al., 2012). For instance, it is observed in maize crops a considerable downhill on photosynthesis due the compromise of light interception as this metabolic mechanism is damaged, either by provoked leaf expansion reduction or premature senescence of aerial parts, both related with water stress (Bruce et al., 2002).

4.3. Crop modelling and biophysical process-based simulations

An agricultural system is the assembly of several elements that have as main goal the production of food and energy through crops, making use of Earth's natural resources (Jones et al., 2017). Although agricultural systems are a meaningful subject of study when applied to particular cases within specific circumstances, a more complex and general approach is required when interactions of many agricultural aspects, such as natural resources and crop management should be take into account (Jones et al., 1986, 2017).

For such purposes, process-based crop models (PBC) are widely use in a variety of applications, being already described on several studies across the world (Soler et al., 2007). PBC's are in a scientific point of view, the integration among different subjects covered in agricultural sciences, such as agrometeorology, soil physics and chemistry, crop physiology, assembled in a set of mathematic algorithms that seek to simulate growth, development and yield. Therefore, PBC's are based on calculations performed within the scope of biological processes that encompasses the relation between plants and the surrounding environments (Hoogenboom, 2000).

Crop modelling allows the simulation of different scenarios and the management of production elements, which results in the understanding of the dynamic interactions within the agricultural system, as those models are capable to obtain estimates of crop yield and plant development through several stages (Di Paola et al., 2016; Yin and Struik, 2009).

The computation of biophysical processes that occur inside most of plants cultivated by humans throughout the history, is one of the key features of PBC's, by dynamically simulating in a daily scale and in a mechanistic way, the development of real life crops already well studied by the agricultural sciences (Amouzou et al., 2018; Andrea et al., 2018; Hoogenboom et al., 1994; Rosenzweig et al., 2018). For this reason, such models are well recognized and accepted as a reliable method for quantification of impacts from environmental aspects such climate change and water stress (Marin et al., 2014; Rosenzweig et al., 2013).

Currently, there are several PBC's that simulates maize crop developments under different scenarios and environments. DSSAT/CERES-Maize (Jones et al., 1986), Hybrid-Maize (Yang et al., 2004) and APSIM-Maize (Keating et al., 2003) are the most common used models with constant updates, gaining several improvements as new understandings of maize plant physiology were enlighten through time. Those models have in common that computation process requires daily meteorological data, soil characterization, information regarding crop management practices and genetic parametrization inputs (Bouman et al., 1996; Di Paola et al., 2016).

For a general overview of the crop model approached for the writing of this thesis, please check section 5.2.

5. MATERIAL AND METHODS

5.1. Field experiments and crop model adjustments

In order to observe the effect of climatic variability over the crop, two field experiments were carried: the first being under rainfed conditions in the off-season maize (“safrinha”), while the second was carried out under the irrigated and rainfed treatments during the summer season (or “in season” maize), which allowed us to evaluate the performance of growth models in representing the effect of climate on plant development under different water conditions.

The experiments were carried in the municipality of Piracicaba/SP, at the Department of Biosystems Engineering of the Escola Superior de Agricultura “Luiz de Queiroz” (ESALQ/USP), located at latitude 22º42'32"S, longitude 47º37' 45"W and altitude of 548 m, in a currently available area of 3 ha, where a sub-area was delimited for the experiment. The first experiment was installed on 06/09/2016, with the harvest being carried out on 10/20/2016. As for the experiment installed during the summer season, it was started on 11/29/2018, and harvested on 03/27/2019. The experimental design used was randomized blocks, distributed in 2 blocks, totaling 4 experimental parcels.

The main objective of such evaluations was to observe the production capability in highly responsive hybrids. Therefore, in partnership with Limagrain Seeds, we were able to use genetic materials with high technology, thus for the essays in 2018/19 and 2019/20, the hybrids LG 36790, LG 36610 and LG 36600 were chosen. To monitor meteorological conditions at the canopy level, a weather station installed near the experimental area recorded global solar radiation (Rg, MJ m-2 day-1), photosynthetic photon flux density (PAR, MJ m^{-2} day^{-1}), air temperature (ºC), relative humidity (%), wind speed ($m.s^{-1}$) and rainfall ($mm.day^{-1}$).

Similar trials were carried out at Júlio de Castilhos/RS, Tupanciretã/RS and Rio Verde/GO, in partnership with the Federal University of Santa Maria/RS. Information from different regions may increase the representativeness of the crop model used.

Table 1. Sources of experimental data used and climate characteristics of each site.

Site	Coordinates	Sowing dates	Harvest Dates	Maturity group	Plant population (10^3 pl ha^{-1})	Climate[1]	Soil[2]	Treatments
Rio Verde/GO	17° 47' 50'' S, 50° 54' 0'' O, 739m asml	16 Feb. 2019	16 Jun 2019	Early	51; 52	22.9 ºC, 432 mm, Aw	Ferralsol	Rainfed
Piracicaba/SP -1	22º 43' 30" S, 47º 38' 49" O, 524m asml	09 Jun. 2016	19 Oct. 2016	Early	70	19.5 ºC, 98 mm, Cwa	Nitisols	Rainfed and Irrigated
Piracicaba/SP - 2	22º 43' 30" S, 47º 38' 49" O, 524m asml	29 Nov. 2018	27 Mar. 2019	Early	70	25.5 ºC, 302 mm, Cwa	Nitisols	Rainfed and Irrigated
Júlio de Castilhos/RS-1	29° 13' 37'' S, 53° 40' 57'' O 513 asml	28 Aug. 2017	21 Jan. 2018	Super-Early	75	20.8 ºC, 762 mm, Cfa	Acrisols	Irrigated
Júlio de Castilhos/RS-2	29° 13' 37'' S, 53° 40' 57'' O 513 asml	07 Sep. 2018	26 Jan.2019	Super-Early	60;80	21.2 ºC, 774 mm, Cfa	Acrisols	Irrigated
Tupanciretã/RS	28º 36' 0" S, 53º 40' 12" O, 427m asml	28 Nov. 2018	24 Jan. 2019	Super-Early	80	23.4 ºC, 410 mm, Cfa	Acrisols	Irrigated

[1] Average air temperature during the experiments, accumulated rainfall and Koppen climate classification, respectively; [2] WRB/FAO Classification.

The calibration procedure was based on Marin et al. (2011), considering the cultivar of measurements taken and different measurement strategies in each dataset, the leave-one-out cross-validation method (Makowski et al., 2006) of data splitting was used to simultaneously include all the variability of conditions and measurements in the parameter estimation and evaluation of the model predictions. The leave-one-out cross-validation procedure had a factorial design in which each run missed one treatment each time. The parameters set derived from these cross-validation runs were used one at a time to evaluate the predictions for phenological stages and grain yield observed during the experiments were used to calibrate the crop model parameters by eye-fitting using the root mean square error (RMSE), mean absolute error (MAE) (Loague and Green, 1991), the index of agreement (d) (Willmott et al., 2012), and the Nash-Sutcliffe efficiency index (NS) (Nash and Sutcliffe, 1970) as measures of goodness-of-fit.

5.2. Brief model description

In order to represent Brazilian crops and estimate their yield gaps, we used the process-based crop model Hybrid-Maize (Yang et al., 2004), which combines growth and development functions specific to maize crops with mechanistic processes that involve the quantification of photosynthesis and respiration. Briefly, model functions for crop growth and development are strongly based on previous crop models largely adopted and tested on several studies (Jones et al., 1986; Kropff and Van Laar, 1993; Van Ittersum et al., 2003).

Photosynthesis, light interception and CO2 assimilation are computed for each layer in the canopy and their relationships with temperature are adapted from Kropff and Van Laar (1993). Maintenance and growth respiration follows a similar approach from INTERCOM (Kropff and Van Laar, 1993), where the process for each organ is estimated as fraction of live biomass in a daily step, but coefficients of growth respiration for leaf, stem, root and grains were adopted from Penning de Vries et al. (1989). Grain-filling functions consider plant population, since individual grain weight decreases in cereal crops as plant density increases (Haegele et al., 2014). Water balance and soil water dynamics are computed for each layer of 10 cm in the rooting zone from top to bottom, in a way that the top layer assumes daily rainfall/irrigation, water losses from runoff and canopy interception as input values, and for the other layers, inputs are accounted as drainage from the layer immediately above, as described in Driessen and Konijn (1992).

Hybrid-Maize only uses one hybrid-specific parameter is required in two separate ways: growing degree-days (GDD) from emergence to silking or the total GDD from emergence to maturity. Therefore, an adjustment of a single generic genotype for representing phenotyping variations across locations is facilitated by defining only one value for GDD that statistically matches simulation outputs and observed data of different regions.

5.3. The Yield Gap Atlas Phase

The Atlas of the yield gap for maize in Brazil was carried out in a joint work between researchers from ESALQ, Embrapa and the Federal University of Santa Maria (UFSM), in Rio Grande do Sul, in accordance with the international protocols proposed by the University of Nebraska (UNL), in Lincoln (USA).

The effort consisted mostly of reviewing the information previously entered in the Atlas, focusing on the yield potential limited by water (Yw) regarding information about the “off-season” crop commonly practiced by Brazilian producers, which until then had been little explored in the first version.

In order to supervise the progress of activities and assist in the generation of relevant information to update the Atlas, periodic meetings were held between July 2018 and January 2020. The main objective of these meetings, in addition to verifying the consistency of the data obtained, was to ensure that the protocols practiced in Brazil were in accordance with all the guidelines followed by almost 50 countries that contributed with information for several crops covered. Thus, all the steps presented here were discussed exhaustively by the group of researchers responsible for representing faithfully the conditions and production gaps for Brazilian maize.

Once crop model simulations were performed, the outputs were organized and information on grain yield potential without limitations (Yp), grain yield potential limited by water (Yw) and the gap between potential and actual grain yields (Yg) were obtained for each representative region of maize production in Brazil by averaging the estimated yield using as weight the proportion of soils containing inside a buffer (see section 2.4 for a full explanation of how those regions/buffers were defined).Yg was calculated by the difference between Yw and the actual yields (Ya), where Ya was obtained by the average data from the last 20 years.

5.4. Climatic homogeneous zones (CZ)

According to the protocols suggested by the GYGA project, the national production of a given crop can be quantified through representative buffer zones. In order to define the locations and quantity of CZ’s to be used, some factors must be considered. The definition of each CZ takes into account the producing regions in the national territory, the climatic homogeneity between these regions according to the methodology established by Van Wart et al. (2013), the presence of meteorological stations within a minimum radius of 100km and, finally, information on the predominance of different types of soil within the representative area of the buffer zone.

To fulfill all above mentioned criteria, datasets from several public sources were used to provide specific information related to agricultural and economical aspects, as well the water usage of every Brazilian municipality. Data required to identify regions with substantial maize production, was provided by the Automatic Recovery System from the Brazilian Institute of Geography and Statistics (IBGE)(SIDRA, https://sidra.ibge.gov.br/).

Acknowledging the possible lack of measured weather data within the CZs, daily weather data was retrieved from NASAPOWER API Client (Sparks, 2018) for filling the gaps in 20 years (2000-2020) of daily datasets provided by the National Institute of Meteorology from Brazil (INMET, 2015). We assumed that the municipality near to the center of a given CZ hosting a weather station (WS) would represent the entire CZ in terms of climate variability. Evapotranspiration data was required by Hybrid-Maize and it was estimated following methods proposed by Allen et al. (1998).

Soil data were extracted from the Brazilian Soil Map (EMBRAPA, 2014) and crossed with the selected CZs. Only soils with more than 10% of coverage were accounted for to avoid over-fragmentation and small soil patches that are not as representative of regional productions. After the soil types identification, all information obtained was checked at the WISE Global Soil Profile Database (Batjes, 2002), in order to determine the physical characteristics of top and subsoil, necessary to perform the crop model simulations.

For the phase of inserting new data regarding Brazilian maize production into the Yield Gap Atlas, Climate Homogeneous Zones were hereby described as CZ_1. In parallel, the steps described in section 5.5 were additionally applied to identify areas for expansion maize irrigated production in Brazil, hence resulting in a different set of Climate Homogeneous Zones, here defined as CZ_2.

5.5. Criteria for selecting potential expanding areas

Due to concerns with minimizing the impacts on natural water sources caused by the expansion of irrigated production, a framework was established by Ferrarini et al. (2019) for identifying the already existing producing areas in order to select the most suitable locations for potential expansion. The methodology consists on defining criteria that encompasses the different aspects of socioeconomic and agricultural diversity of Brazil. Thus, the following criteria steps were used and Fig 1 shows the information flowchart that support our analysis scheme:

a) The municipality must produce soybeans during the summer flowing by off-season maize: the starting point for this selection was based on an economic criterion and the potentiality of agricultural areas, since in farms where soybean is grown, obstacles such as production logistics, machinery and inputs spent for maize cultivation would be easily resolved. Following the same idea, areas of off-season maize must be equal or smaller than those used for soybeans, by that the new areas of off-season maize would be implanted where the soybeans would already exist and the off-season crop area would be still vacant.
b) Municipalities must already have irrigated crops: it is assumed that not all locations that fit the previous criteria have water resources capable of supporting irrigated systems. In this way, irrigated areas would have less obstacles for irrigation, or even already have infrastructure installed within croplands suitable for use in new off-season maize areas (Beare et al., 1998; Giannakis et al., 2016).
c) The estimated irrigated volume required for the crop might be less than the limit of 95% of the flow of the watercourse (Q95) (irrigation capacity): one must account that the efforts for closing production gaps should require approaches that consider environmental practices on dealing with water resources (Grassini et al., 2011b).(Grassini et al., 2011b)

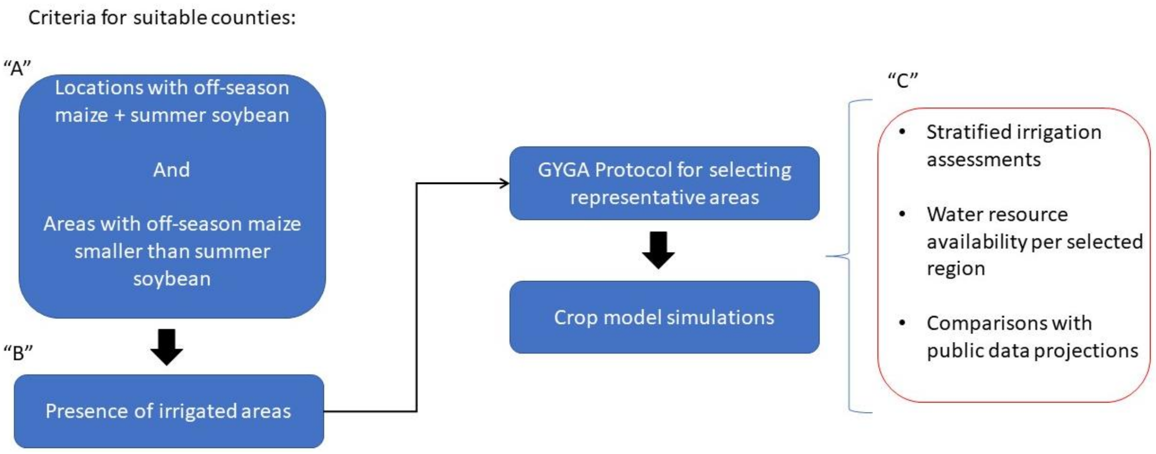

Figure 1. Steps followed on quantifying available water for potential new off-season maize areas, in accordance with the defined criteria.

Data of maize and soybean production, growing area and yield at county scale, required by criteria "A", was provided by the Automatic Recovery System from IBGE

(SIDRA, https://sidra.ibge.gov.br/). Data required for criterion "B" were obtained from Brazilian Irrigation Atlas of Brazilian National Agency of Waters (ANA, 2017). The water flow of river basins, regarding the criterion "C", were provided by ANA's metadata library from National System of Information about Water Resources (SNIRH, 2017). All datasets have been considered as a time scale of 5 years (2015 to 2020), which is intended to represent current conditions upon maize production is found in Brazil.

Once the mentioned criteria were met and locations were well defined for all CZ's, crop model simulations were performed for each weather-soil combination. Sowing dates and plant density for each location follows in the governmental reports (CONAB, 2021) (Supplementary Table S1). Simulations were first carried out for mimicking a full irrigated maize cropping system, and the generated output files were then read for retrieving the irrigated volume in each simulated day. Following, a new set of simulations were done with irrigations being applied at the same days, however with stratified water amounts ranging between 100 and 0% of total irrigation (at steps of 10 percentage points), being the last a representation of rainfed conditions. The reason for such an approach consisted in generating a set of simulations with different irrigation levels to be compared with water flow databases from river basins.

5.6. Water requirements and irrigated area quantification

Two approaches were followed for analyzing the stratified amounts of irrigation mentioned at the end of section 5.5: the first evaluated what would be the partially/full-irrigated yield potential (Ypi) obtained by simulating different amounts of irrigation, and how it would differ from rainfed yields (Yw). This would allow a detailed classification of each potential new area in terms of water supplementation by irrigation. The second path estimated the amount of available natural water resources for irrigation as a percentage of expandable new areas in the given CZ: as applied water is given in millimeters (i.e., L m^{-2}), knowing the locations and size of potential new areas, this can be matched with data related to available water resources in order to determine how much area in each CZ would be able to be irrigated. This analysis was made considering at first, only potential new off-season maize areas and then the total areas where maize crops are practiced.

Lastly, based on the irrigation levels described in topic 2.3 of each CZ, we also estimated the total expandable area under full irrigation and how much it would increase the national production and in what measure it would close the maize yield gap between current production and the achievable potential, as reported in the Global Yield Gap Atlas (GYGA) (https://www.yieldgap.org/brazil). Those estimations were compared with public data sources about irrigation expansion (ANA, 2017) to assess if governmental policies would meet the requirements in order to properly fulfill future grain demands.

For comparing differences of Ypi from the considered amounts of irrigation in regard to rainfed estimations, we performed the Tukey test (Tukey, 1953) at 5%. This approach has the purpose of evaluating whether in a single CZ the water consumption increase will bring significant gains on crop production, and consequently, provide estimations of how much irrigation is required to expand in order to achieve average yields necessary to close the Brazilian agricultural gaps for maize.

6. RESULTS

6.1. Model calibration and evaluation

Simulations well-compared to observed data, diverging in less than 1.21 Mg ha^{-1} for grain yield (Fig. 2). For phenological data, RMSE were higher, despite still being at acceptable levels of agreement (Tab. 2). It was assumed that modern maize genotypes deal with environmental variability in a similar pattern, therefore the differences among simulated yields, and mainly phenology, were inferred as residual deviation occurred by management actions at the experimental level i.e., irrigation, planting dates and soil properties.

Best fit estimates were obtained by changing the standard value for the potential number of kernels per ear parameter, in the Hybrid Maize model. By standard, the model has set this parameter at 675 grains per ear, although the better representation from experimental observations was set at 736 grains per ear. This number was defined by evaluating 95% of individuals in a sample set of 304 ears obtained from the experiments (Fig. 3). Additionally, by setting the GDD model parameter in 1553 degree-days, the statistical indexes were improved with satisfactory agreement between observed and simulated data (Tab. 2).

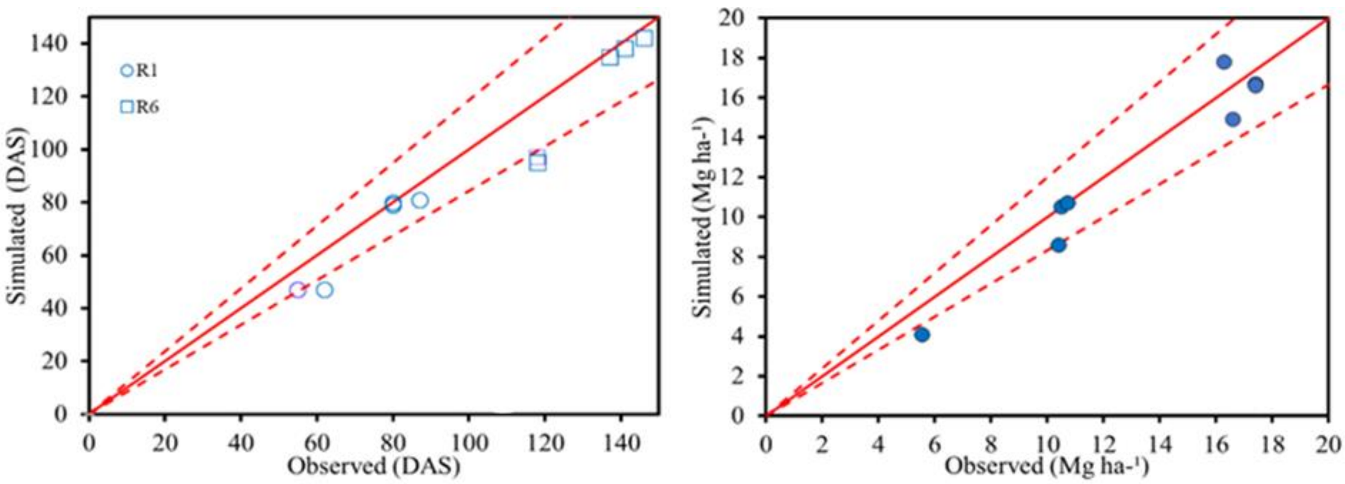

Figure 2. Model performance evaluation on representing phenology (left) and grain yield (right) from the observed data across regions in Brazil.

Table 2. Statistical measures of goodness-of-fit of the crop model validation.

Output	R^2	RMSE	MAE	d	NSE
Grain yield	0.95	1.211	1.001	0.88	0.91
Phenology	0.93	11.412	7.892	0.86	0.86

R^2: coefficient of determination; RMSE: root mean squared error; MAE: mean absolute error; d: Willmot index of agreement (Willmott et al., 2012); NSE: Nash-Sutcliff index of efficiency (Nash and Sutcliffe, 1970).

[1] Measured in Mg ha^{-1}; [2] Measured in days.

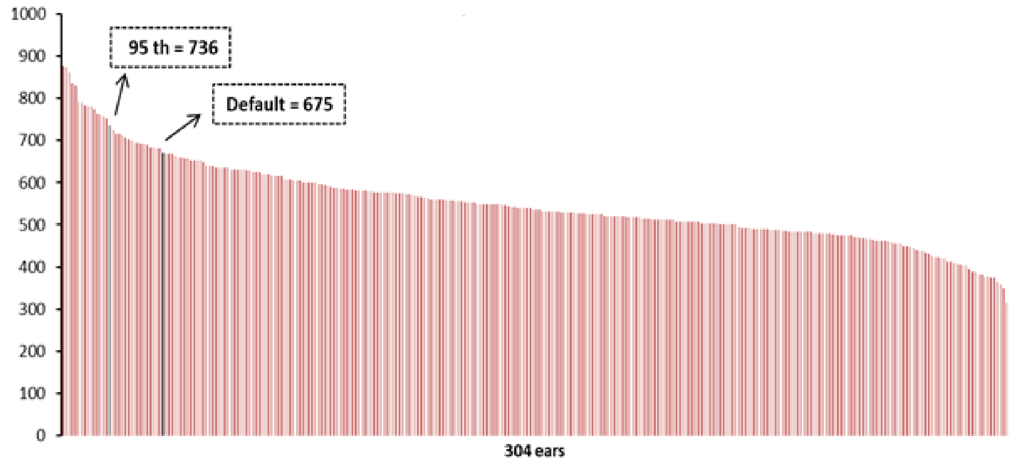

Figure 3. Number of grains per ear obtained from a sample of 95% of field observations.

6.2. Yield Atlas Update

A total of 25 CZ_1's was defined by the method described in Section 2.3, which must represent at least 50% of all national maize production (Figure 4). This representation methodology aimed to facilitate the execution of simulations from computer models.

Figure 4. Results of the buffer selections for all main maize producing regions from Brazil.

The simulation results showed that during the “off-season”, the producing regions of northeastern Brazil (CZ_1's 3 and 4) have lower yield potential, since in this cropping system there are prolonged periods of water stress (Figure 5). Both in the “summer” and “off-season”, most of the producing regions are concentrated in the Midwest, Southeast and Southern regions of Brazil, displaying in the majority of CZ_1’s a yield potential above 10 Mg ha^{-1}.

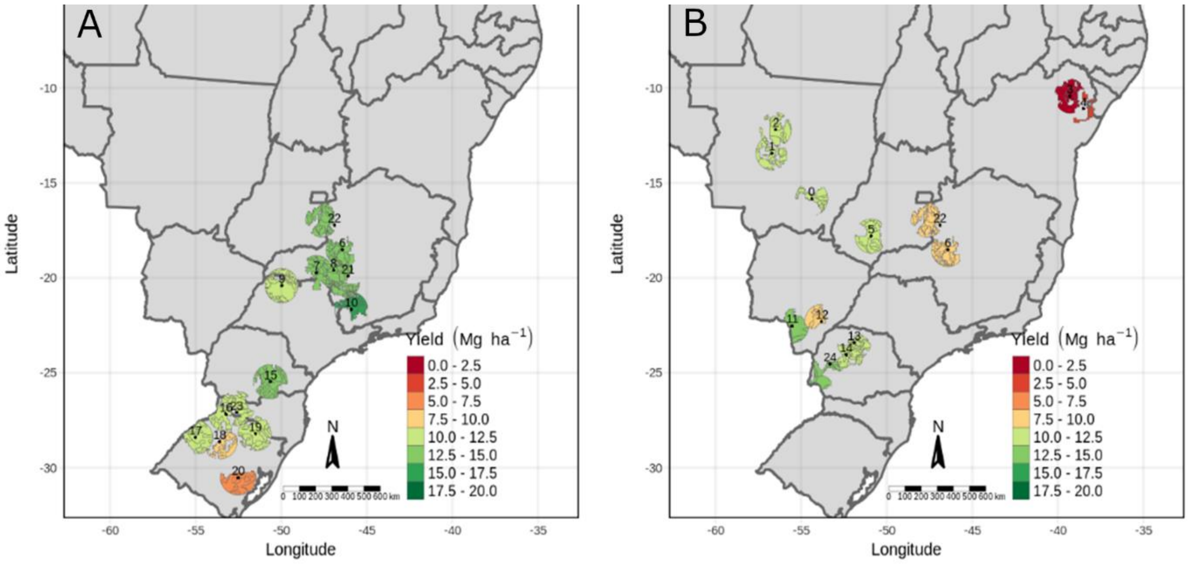

Figure 5. Yield potential limited by water (Yw) for crops during (A) “summer” e (B) “off-season”.

When analyzed by the relationship between Ya and Yw, for the majority of producing regions during the "summer" are contained in the Center-South axis of Brazil, which achievable yield ranging between 60 to 80% of the potential, while for crops in "off-season" there are values of Ya below 40%, showing that water stress is one of the main limiting factors for this period (Figure 6).

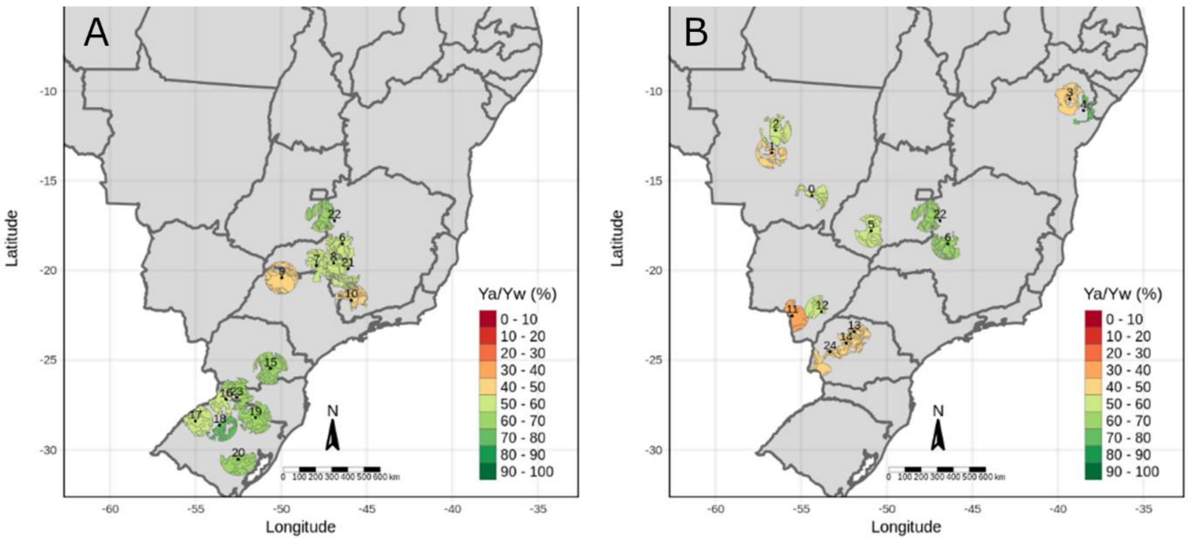

Figure 6. Ratio between actual yields (Ya) and water-limited yield potential (Yw) for crops during “summer” (A) and “off-season” (B).

In general, the "summer" maize crops had the highest yield potential and the greatest differences in terms of achievable yields. On average, for this season, the yield gaps are nearly 5.2 Mg ha^{-1}, or in other words, has the possibility of expanding the production by 41.9% without the need to open new production areas (Tab. 3). CZ_1 9 and 10 showed the greatest differences between Ya and Yw, which points to possible areas that present greater lack of investments for crop intensification. On the other hand, for certain regions, the difference between achievable and potential is low, despite it does not necessarily mean high reported yields (Tab. 3). The CZ_1 18 and 20, represented by the meteorological stations of Cruz Alta/RS and Encruzilhada do Sul/RS, respectively, have a small difference between Ya and Yw, however the potential obtained through the models is low when compared to the other regions, showing that for in these places, maize crops might be close to the genetical limit intended for its development (Tab. 3).

Table 3. Description of water-limited yield potential (Yw), actual yield (Ya), yield gap (Yg) and the ratio between Ya and Yw, for CZ1's during "season".

CZ	Met. Station	Yw (Mg ha^{-1})	Ya (Mg ha^{-1})	Yg (Mg ha^{-1})	Ya/Yw (%)
6	Patos de Minas	14,96	7,99	6,97	53,42
7	Uberaba	14,54	7,98	6,56	54,86
8	Araxa	14,82	7,9	6,91	53,34
9	Votuporanga	11,67	5,28	6,39	45,27
10	Machado	15,08	6,03	9,05	40,01
15	Irati	12,96	8,15	4,81	62,9
16	Irai	10,88	6,37	4,51	58,57
17	Sao Luiz Gonzaga	10,45	5,85	4,6	55,99
18	Cruz Alta	8,16	6,4	1,76	78,38
19	Lagoa Vermelha	11,86	7,37	4,48	62,21
20	Encruzilhada do Sul	5,47	3,56	1,91	65,06
21	Bambui	13,88	7,01	6,86	50,55
22	Paracatu	13,97	9,38	4,58	67,18
23	Chapeco	11,84	7,82	4,02	66,06
Mean		12,2	6,9	5,2	58,1

For "off-season" maize (Tab. 4), the yield gaps estimated were smaller when compared to the "season", however, the potentials were also lower for most regions. In a few CZ_1's, there is still a considerable difference between Ya and Yw, denoting a strong impact of water deficit, as occurs in CZ_1's 11, 13 and 24, on which the improvement of crops through irrigation would probably bring significant gains for these regions. The CZ_1's 3 and 4, represents two productive regions of Northeast Brazil and stand out for their low yield potential in regard to other locations, during the "off-season". Moreover, the possible differences between potential and current yields are mainly due to genetic limitations of crops for developing in the mentioned areas. The updated information regarding Brazilian maize and other crops, are already available to access in the project's website, through the link: http://www.yieldgap.org/Brazil.

Table 4. Description of water-limited yield potential (Yw), actual yields (Ya), yield gaps (Yg) and the ration between Ya and Yw, for CZ1's during "off-season".

ZCH	Met. Station	Yw (Mg ha^{-1})	Ya (Mg ha^{-1})	Yg (Mg ha^{-1})	Ya/Yw (%)
0	Poxoreo	10,64	5,86	4,78	55,05
1	Sao Jose do Rio Claro	11,22	5,49	5,74	48,88
2	Gleba Celeste	10,6	5,3	5,3	50,02
3	Monte Santo	1,98	0,85	1,13	42,71
4	Cipo	4,49	3,16	1,33	70,34
5	Rio Verde	10,03	5,68	4,35	56,64
6	Patos de Minas	7,54	5,07	2,47	67,23
11	Ponta Pora	12,8	4,85	7,95	37,89
12	Ivinhema	8,97	4,84	4,13	53,93
13	Maringa	10,73	4,92	5,81	45,88
14	Campo Mourao	12,25	5,44	6,81	44,43
22	Paracatu	8,48	5,43	3,04	64,12
24	Cascavel	12,65	5,58	7,08	44,07
Média		9,4	4,8	4,6	52,4

6.3. Representative selected areas

The application of the selection criteria (Fig. 7A and 7C) resulted in a total of 22 CZs, spread across 11 Brazilian states and representing 81% of the area where off-season maize and soybean production is concentrated, with potential for irrigation. The selected areas are in accordance with current producing areas according to government agencies (CONAB, 2021;

IBGE, 2019). The complete list of CZs, with their respective hypothetical WS and soil types, are described in Table 5.

Despite the geographical proximity of the identified CZs in Northeastern Brazil, this variability in nearby areas can be explained by the presence of a transition zone of at least 3 biomes (Amazon Forest, Cerrado and Caatinga) (Arruda et al., 2017; Calmon, 2020), inferring a considerable climate disparity between measurements among WS's in the region.

As described in Table 5, off-season maize production at Southern regions was most present at latitudes above -25º, in which temperatures and rainfall (Tab. 6) are still close to optimal ranges for sustain crops throughout the autumn (Supplementary Table S2). In Mid-western Brazil, production areas are concentrated near the WS's identified in latitudes ranging from -18º to -12º (Fig 7C), also containing a great number of river courses (Fig. 7B), indicating the presence of areas more suitable to irrigation without depleting water resources. On the other hand, Northeastern areas have lesser availability of river water resources, which may lead to higher difficulties to incorporate irrigated systems, therefore crops may reach lower yield led by water deficit stress.

Table 5. Location of the hypothetical weather stations within homogeneous climate zones (CZ) with the amount of type of soils covered in a 100km buffer.

Long	Lat	CZ	County/State	Soils	Long	Lat	CZ	County/State	Soils
-55.71	-22.04	1	Ponta Porã/MS	2	-46.53	-8.50	13	Balsas/MA	5
-45.97	-17.54	2	João Pinheiro/MG	3	-45.84	-8.28	14	Tasso Fragoso/MA	3
-45.42	-16.37	3	São Romão/MG	4	-44.75	-9.13	15	Bom Jesus/PI	2
-48.56	-23.71	4	Buri/SP	5	-45.49	-8.13	16	Ribeiro Gonçalves/PI	2
-48.79	-23.94	5	Itapeva/SP	3	-43.98	-7.51	17	Sebastião Leal/PI	3
-47.52	-16.73	6	Cristalina/GO	2	-45.41	-11.90	18	Barreiras/BA	1
-58.00	-12.27	8	Brasnorte/MT	3	-51.02	-17.70	19	Rio Verde/GO	2
-52.53	-12.34	9	Querência/MT	3	-52.80	-24.59	20	Campina da Lagoa/PR	1
-55.69	-12.70	10	Sorriso/MT	4	-53.24	-24.73	21	Corbélia/PR	5
-46.84	-8.22	11	Campos Lindos/TO	3	-60.60	-13.54	22	Cabixi/RO	4
-46.11	-9.54	12	Alto Parnaíba/MA	3	-61.60	-13.11	23	Pimenteiras Do Oeste/RO	4

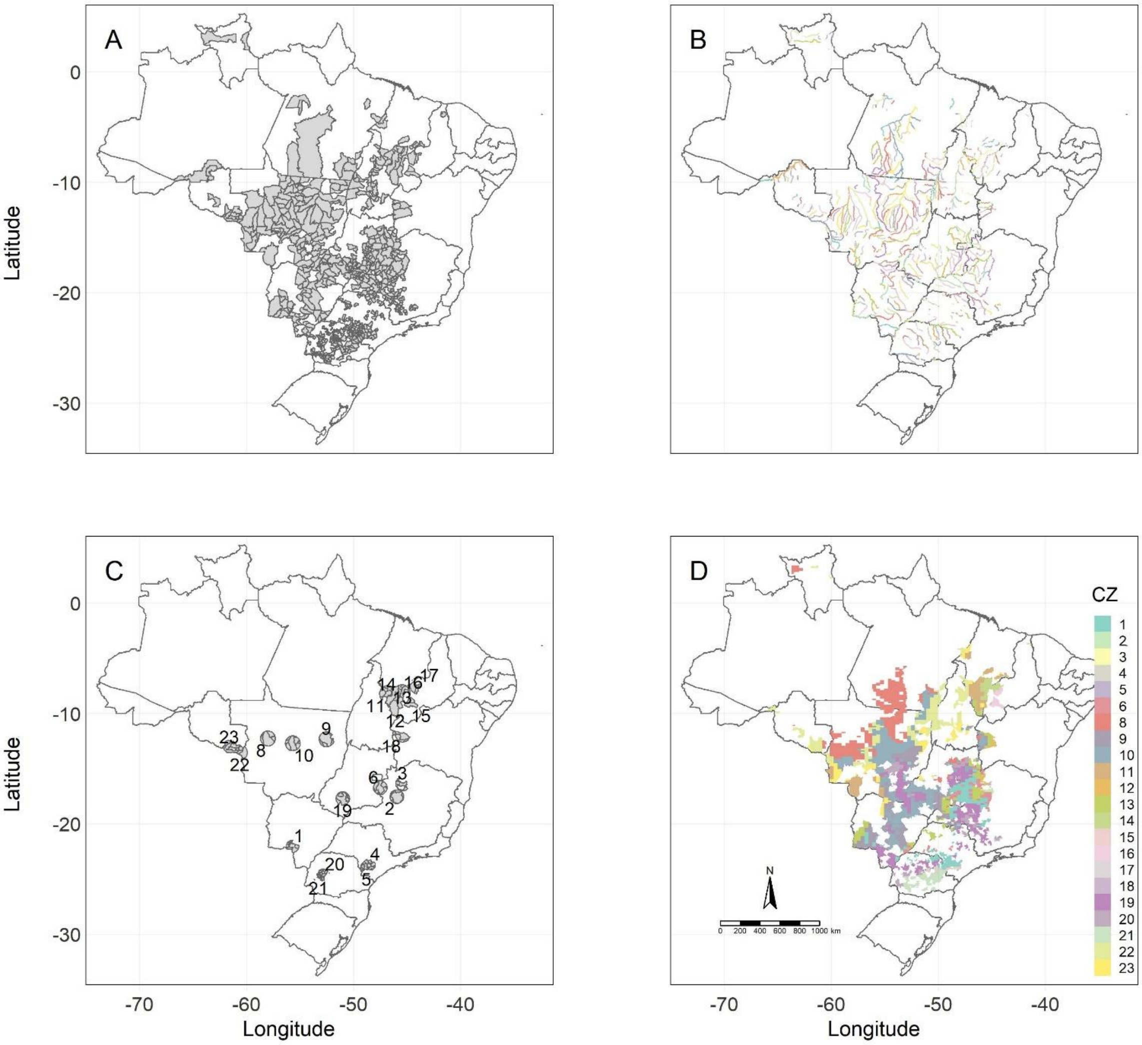

Figure 7. (A) Counties selected by criteria 1 to 3, with (B) their respective water resources containing a reported water flow data, Color variation only illustrated the many different river watercourses present inside the potential areas. (C) Representative weather stations which contain covered selected representative soils in a 100 km buffer. (D) Homogeneous Climate Zones (CZ_2's) distribution across selected production counties in Brazil.

6.4. Yield potential and water requirements

The Yp across the country for off-season maize ranged from 5 to 17 Mg ha^{-1}, requiring an average of 20 up to 180 mm of irrigation for achieving such grain production per area cropped (Fig 8). The highest yields were identified at Southern latitudes, covered by CZ_2's 6,5,4,19 and 20, where average estimated yields reached values higher than 15 Mg ha-1 (Fig 8A). Lower yields were found at Northeastern production regions, where CZ_2's 17, 15, 16, 14 and 13 obtained an average grain yield potential below 7 Mg ha^{-1}. The disparity between Southern and Northern Ypi (Tab. 6), is mainly caused by poor physical properties for soils. Moreover, Southern and Mid-western crop lands have soils with better physical conditions for water storage, and therefore benefits for plant growing at seasons with low rainfall. Consequently, irrigation requirements for yield potential productions were lower in the South and Mid-western locations than Northern and Eastern ones (Fig 8B). The CZ_2's 8, 11, 14, 9 and 10 showed, on average, the lowest amounts of irrigation applied, always being below 35 mm per cycle. The highest quantities were estimated for CZ_2's 18, 22, 23, 2 and 6, where irrigation requirements were above 100 mm per crop.

Table 6. Mean air temperature (TMed), average accumulated rainfall (Rain), crop evapotranspiration (ET), irrigation (Irrg) and solar radiation (SRad) during crop cycle, followed by the estimated average Yield Potential by irrigation (Yp_i), for each CZ, considering a time-scale of 20 years (2000-2020).

CZ	WS	TMed	Rain	ET	Irrg	SRad	Yp_i
		ºC	mm cycle^{-1}			MJ m^{-2} cycle^{-1}	Mg ha^{-1}
1	Ponta Porã/MS	23.5	503.2	339.9	63.3	2054.6	13.5
2	João Pinheiro/MG	23.4	371.3	330.0	118.5	2312.2	14.5
3	São Romão/MG	25.4	306.7	318.8	101.5	2071.3	12.2
4	Buri/SP	19.2	446.4	390.6	64.6	2586.5	17.6
5	Itapeva/SP	20.9	482.0	356.1	67.7	2365.7	16.4
6	Cristalina/GO	22.1	494.9	351.5	107.2	2466.2	15.6
8	Brasnorte/MT	24.9	612.2	245.4	14.5	1858.7	12.5
9	Querência/MT	25.1	582.0	250.4	33.2	1927.7	12.5
10	Sorriso/MT	24.9	623.1	257.7	33.4	1912.3	12.7
11	Campos Lindos/TO	25.7	588.2	291.1	16.1	1753.0	11.5
12	Alto Parnaíba/MA	25.6	334.5	259.9	58.9	1873.0	6.9
13	Balsas/MA	25.9	400.7	247.6	43.3	1771.0	6.9
14	Tasso Fragoso/MA	26.3	342.9	263.0	31.0	1763.4	6.5
15	Bom Jesus/PI	26.7	265.7	266.7	68.9	1799.9	6.3
16	Ribeiro Gonçalves/PI	26.4	312.0	267.1	37.7	1761.0	6.4
17	Sebastião Leal/PI	27.4	260.6	260.2	48.0	1683.3	6.0
18	Barreiras/BA	25.0	97.9	273.1	187.9	1993.7	7.4
19	Rio Verde/GO	22.7	554.9	335.0	80.6	2277.1	15.3
20	Campina Da Lagoa/PR	21.0	611.3	355.0	46.7	2335.7	15.7
21	Corbélia/PR	21.8	566.6	362.1	41.9	2239.2	14.9
22	Cabixi/RO	24.4	181.1	261.2	137.7	1852.1	11.8
23	Pimenteiras Do Oeste/RO	25.3	178.0	239.5	119.0	1743.2	11.1

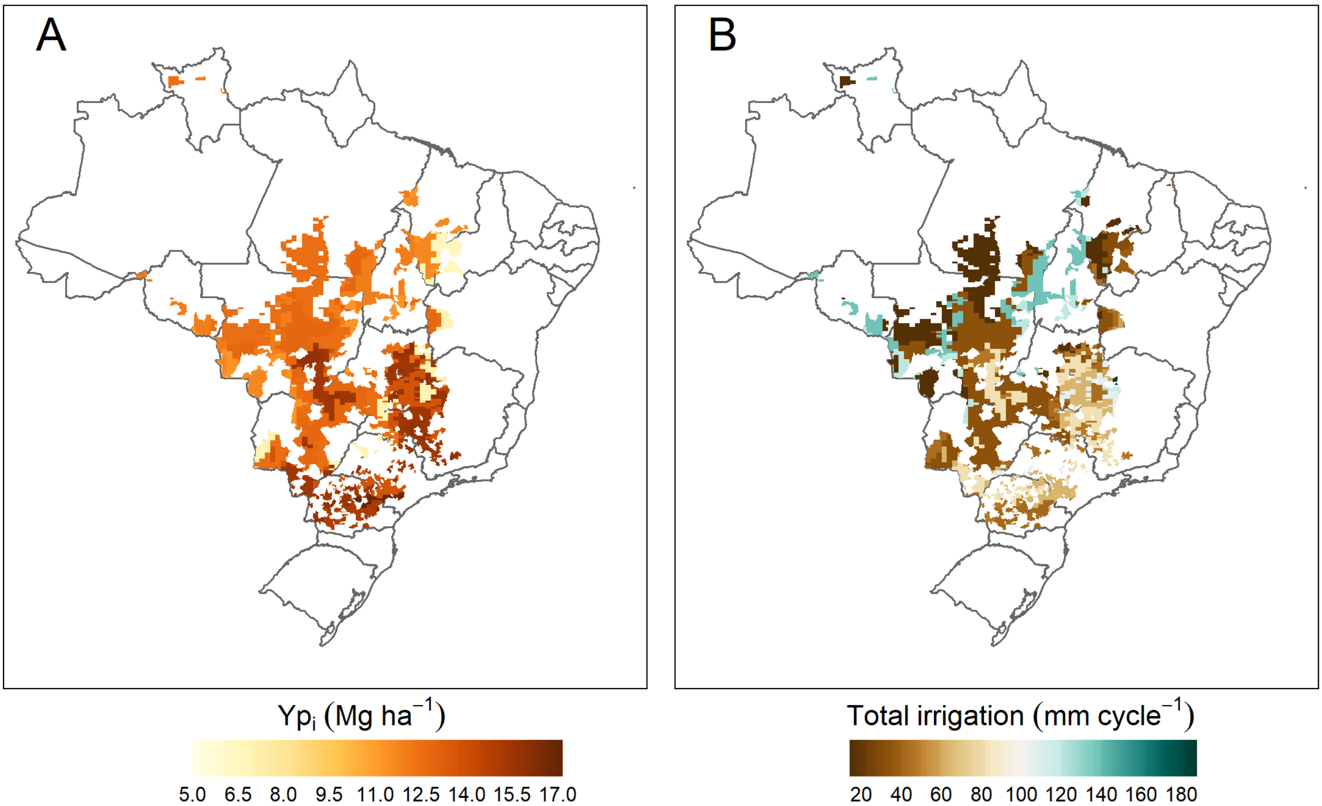

Figure 8. (A) Yield potential achieved by irrigation (Ypi) and (B) average irrigation amount per cycle necessary for fulfil all water requirements in the field during the cycle.

6.5. Potentiality of off-season maize expansion through irrigated areas

The stratified analysis of irrigation capacity showed regions with high variability in terms of closing rainfed and irrigated production gaps (Fig. 9A). The CZ_2's 18, 22 and 23 showed higher Ypi at the cost of greater amounts of irrigation, as water availability represents almost 100% of the difference between Yw and Ypi. On the other hand, regions represented by CZs 8, 14 and 11 showed little response to irrigation, since the Yw and Ypi differ by less than 15%, as rainfall reaches acceptable levels for water supplementation throughout the season (Tab. 6). In the remaining CZ_2's, rainfed and total irrigation yields differ between 50 and 70%, occurring mainly in locations with high Ypi under relatively lower water demand. High water demand, in contrast, was identified in Northern and Northeastern areas (Fig 9B). However, for some locations, the difference between Ypi and rainfed yields reached lower values, thus representing small gains achieved by irrigation (e.g., CZ_2's 15 and 17).

When comparing the grouped difference between crop water regimes, CZ_2's 8, 14, 16 and 17 presented no statistical differences between Ypi and Yw (Fig. 9B). Still, for most of

CZ_2's, significant production gains only will be reachable by irrigating above 50% of the potential areas able for off-season maize expansion. The CZ_2's 22 and 23 showed significant differences from Yw after 30% of areas irrigated, meaning that cropland areas represented inside those regions would be more responsive to irrigation. The CZ_2's 1, 9, 10, 11 and 20 are regions in the Mid-western and Southern Brazil, and according to Table 3, the estimated irrigation required for crops to achieve their yield potential is below 65 mm, although Fig. 9B shows those locations with significant differences from rainfed yields by irrigating above 70%, therefore pointing to areas with lower water requirements for achieving full yield potential.

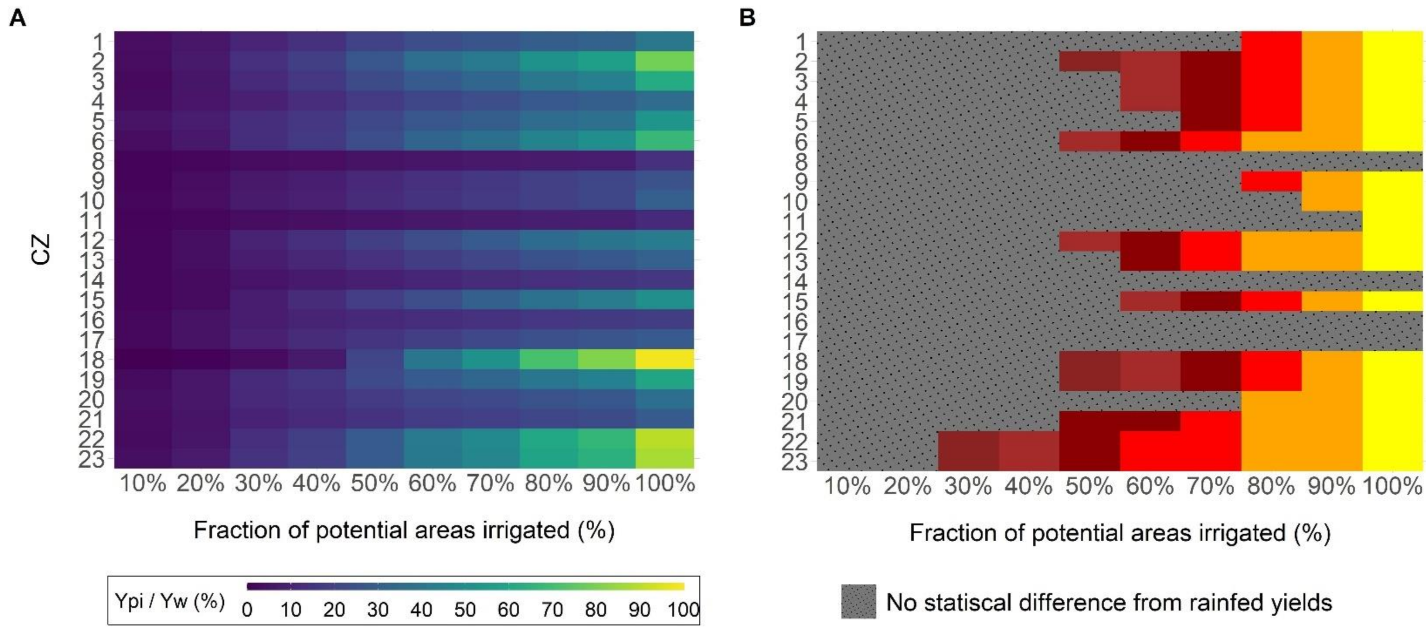

Figure 9. (A) Ratio between Ypi and Yw, by the gradual increase of irrigated areas (X-axis). (B) Grouped difference between yields within CZ2's. Statistical differences are set by color differentiation.

The capacity of water resources to supply irrigated off-season maize reveals that, for most of CZ_2's, the expansion of off-season maize crops to areas occupied by soybeans in the summer will be possible using 10 to 50% of the available volume in water sources (Fig. 10A). However, for the production areas contained in CZ_2 18, a value of 20% of the potential expansion areas can be irrigated without the Q95 limit of available water resources. The CZ_2's 2, 3 and 6, were identified as regions with enough water resources to entirely supply the crop water requirements. Although, Figures 7B and 7C shows that those regions share a few of their water reservoirs due their proximity, thus it becomes uncertain if the calculations in regard to the total water usage are still reliable for this case in specific. The same for CZ_2's 11 to 17, although there were few river basins for those locations and soils with little water retention capacity (Fig 7B and Supplementary Table S1), thus possible water limitations for irrigation are still restricted to their specific cropland.

When including the areas occupied with maize during summer, there was a drastic change in the scenario for some locations. The producing regions in CZ_2 20 could irrigate only 30% of their areas without depleting resources, while in CZ_2 1 the capacity is reduced to a maximum of 20% (Fig. 10B). The CZ_2 19, in the previous scenario (Fig. 10A), had the capacity to irrigate 100% of its area using only 17% of the available water volume, but when considering the additional areas (Figure 6B), the amount used exceeds 85%. For CZ_2 18, irrigation becomes infeasible, once the amount necessary to irrigate less than 10% of the total area will surpass the Q95 limit, threatening the water supplies for the represented regions.

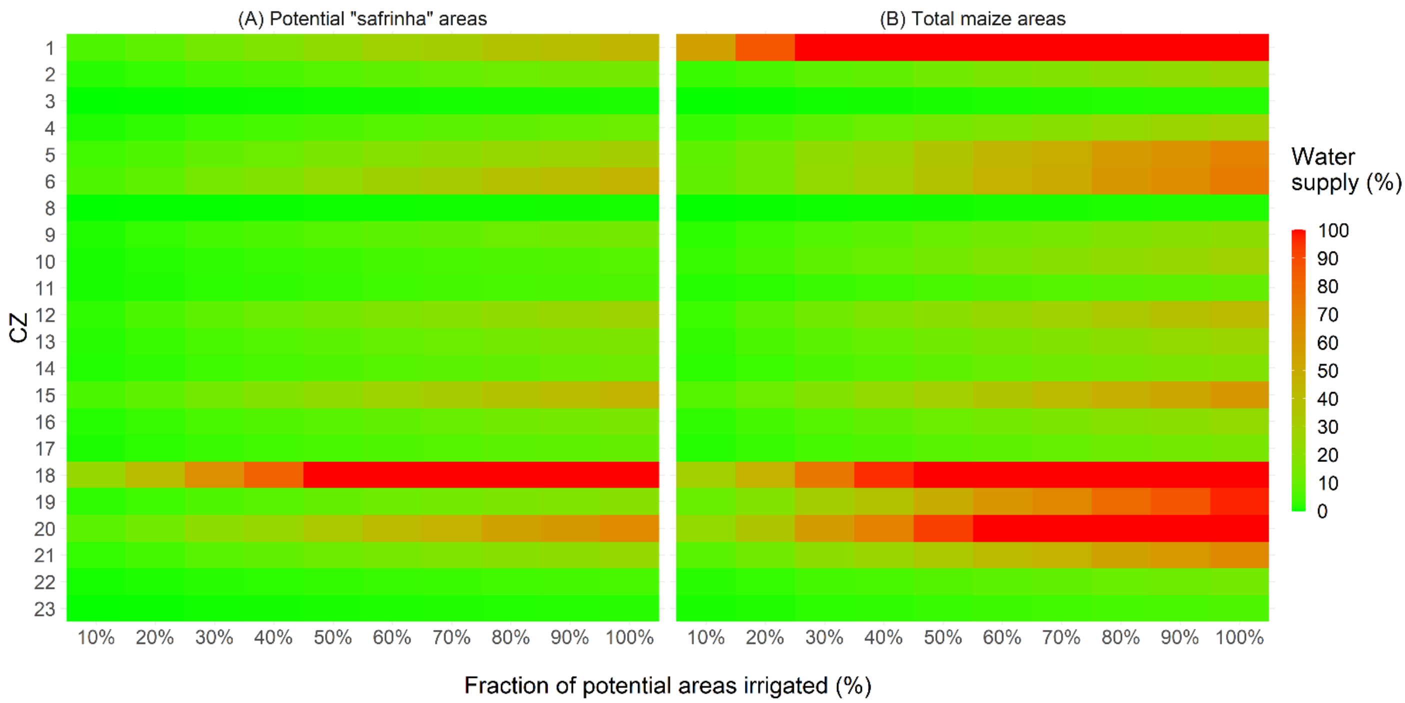

Figure 10. Usage of the available water supply (color variation) as the irrigated areas increases in a given CZ (X-axis), on potential yield for off-season ("safrinha") maize expanding towards soybean areas (A) and with also accounting areas already used for maize crops during the summer (B).

Official reports prospects by 2030 an increase of approximately 3 million hectares (29.6 %) of irrigated maize at the locations identified as potential areas for off-season maize in Brazil (Fig 11A). However, our projections at GYGA indicate that there is still a gap for increasing yields by 55.4% in order to achieve the crop yield potential for current cropland areas. An average increase by this amount on crops is estimated to be reached by irrigating approximately 7.8 million hectares (72.6%) of the selected potential areas (Fig. 11A). The total amount of potential new areas is estimated at around 10.7 million hectares.

Governmental prospects indicated that irrigation expansion in Brazil will bring a significant increase on national average maize yield, crop model estimates are showing that gains will barely surpass the current values obtained from rainfed crops (Fig. 11B). Statistically, an increase of ca. 20% of irrigated areas have shown no difference on yield gains from those obtained in rainfed regimes. Besides, if agricultural goals were set for closing the Brazilian maize yield gap, average increases in crop production would be considered with the irrigation for a minimum of 50% potential areas intended for expansion.

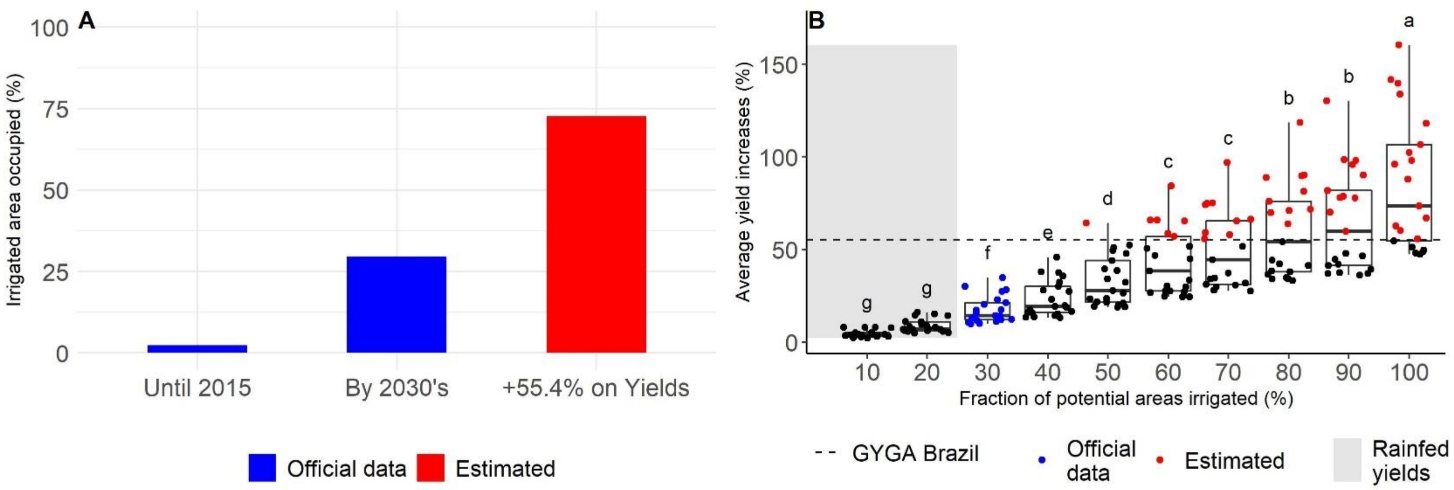

Figure 11. (A) Comparison between official governmental data (ANA, 2017) and estimates about the expansion of potential irrigated areas, including only counties within the selected areas. (B) Grouped statistical difference among CZs.

7. DISCUSSION

Locations with high yield potential at the cost of larger amounts of irrigation such as CZ_2's 18, 22 and 23 (Barreiras/BA, Cabixi/RO and Pimenteiras do Oeste/RO, respectively), denote regions where water stress is shown as a primary factor for grain yield losses. Essays performed with modern maize hybrids showed that drought-tolerant materials had yields depleted from 38 to 55%, in addition to abnormalities on phenology such as longer flowering days and increased length of silk interval (Sah et al., 2020).

Identified areas between northern and northeastern regions are primarily seen as current agricultural frontiers of Brazil (Borghi et al., 2014; MAPA, 2018; Pereira et al., 2018), raising some concerns related to the maintenance of crops due to water limitations. Assessments with soybean (Reis et al., 2020) in succession with off-season maize (Pires et al., 2016) has shown a historical trend of rainfall shortages in those regions during the period where farmers would sow short-cycle soybean in order to cultivate maize in the sequence, resulting in substantial grain yield losses for both crops. The CZ_2's 14 and 11 are located in the mentioned region, also identified as locations with the lowest increase requirements of water volume to expand off-season maize crops. Climate irregularity for this region is seen as a key limitation for potential production (Giachini et al., 2017), where Yp were below 6.5 Mg ha^{-1}. Hence, achieving such yields does not require large supplementary water amounts, and those locations should be considered as a starting point for public policies and irrigation investments. Cunha et al. (2015) pointed out that under climate change scenarios, land values of irrigated areas could rise up to 5% by the 2050s. Therefore, even with small gains on grain yields, payback of public investments can be assured by avoiding significant losses in total maize production (Martins et al., 2019).

In a more sensitive point of view, CZ 18 was identified as a region where yield gaps are largely explained by water demands, although there are only resources enough to irrigate no more than 20% of the potential new areas. Considering the foresaw future scenario where climate change will pose limitations to croplands (Marin, 2014; Müller and Robertson, 2014; Wheeler and von Braun, 2013), weather sensitivity is expected to exceed 50% of yield variations for maize in the United States and seven other major producing countries, with water limitations identified as the main reason for losses (Frieler et al., 2017). Therefore, regions seen with limited water resources for improving cropping yields should be pointed as risky areas where food security could not be self-assured, and efforts to overcome such limitations should be the main focus for policymakers, decision-makers and scientists.

The notion of Yw has already been carried out on several studies aimed to elaborate strategies for improving water efficiency on crops (Passioura and Angus, 2010). Mulching with plastic film between rows has shown considerable yield increases for maize by reducing water losses for evaporation (Zhou et al., 2009), although the labor for laying out the film on the ground could be impractical for farmers and expensive for poor producers. More feasible options for mulching rely on the use of no-tillage systems, which has already been proven as a good way to optimize water efficiency in many studies for maize in Brazil (Baldé et al., 2011; Bergamaschi et al., 2010) and the US (Delate et al., 2012). Managing threats in terms of physiological responses could be also a path to be considered. Techniques such as free-air CO_2 enrichment (FACE) have shown substantial improvements on plant development in water-limited environments (Wall et al., 2006) by restraining stomatal aperture and increasing photosynthetic activity (Field et al., 1995). For maize, experiments using FACE presented significant increases in grain yield (+41%) and biomass (+24%), especially in areas where water is a limiting factor (Manderscheid et al., 2014). However, on large assessments for climate change where scenarios present increases both on air temperature and atmospheric CO_2 concentration, it is still uncertain if physiological gains will surpass temperature stresses (Antolin et al., 2021; Marin et al., 2013; Silva et al., 2021; Souza et al., 2019).Furthermore, maize breeding programs have achieved significant improvements in adapting drought-tolerant genotypes in order to present enough options for farmers on dealing with losses caused by water deficit (Cooper et al., 2014; Maazou et al., 2016; Ribaut et al., 2002).

Nevertheless, even with large assets of information to aid producers to reach the numbers presented in this study, public investments are still required for attending future grain demands. Brauman et al. (2013), pointed out such interventions to raise water usage efficiency to the 20th yield percentile would assure increases in rainfed areas to provide food for around 110 million people, reducing water consumption enough to meet yearly domestic demands for almost 1.4 billion people. With actions aimed to make it easier to access technologies and information towards efficient water usage, current and future irrigated areas will achieve yield gaps ever shorter with the expenditure of fewer quantities of resources than those hereby presented.

On the other hand, in terms of irrigated area expansion, 2030's governmental projections estimate an irrigated area of 10 Mha for all crops in the whole national territory (ANA, 2017), in which nearly 3 Mha encompasses only the potential expansion areas for off-season maize identified in our study. This last projection is far below the irrigated area necessary for an average increase on crop yields by 55.4% for closing the Brazilian maize yield gap (www.yieldgap.org, 7.8 Mha). Therefore, efforts should be considered to appropriately increase public projections. Multsch et al. (2020) assessed that irrigating all current rainfed areas in Brazil will result in an additional 45.56 Mha of irrigated areas, delivering strong impacts on surface water resources. However, the same study pointed out that scarcity levels considered acceptable, comfortable and worrying can be reached by expanding irrigated areas to 16.6 Mha (36.6%), 20.68 Mha (45.4%) and 24.89 Mha, respectively. Thus, in accordance with previous studies, our numbers showed that there would be enough water resources for closing the Brazilian maize yield gaps caused by water deficits.

8. CONCLUSIONS

The CZ_2's locations defined by GYGA methodology replicated here are in agreement with the main production regions known by governmental entities, then it is expected that the information produced would help decision-makers on future strategies in order to close yield gaps. The joint collaboration between scientists and those who can implement agricultural policies, is vital for the efficient use of Earth's natural resources, as well the welfare of key crops for human feed, livestock and world economies.

Crop modeling estimates has shown that there is enough water to irrigate the Brazilian maize fields in order to fulfill limitations of requirements to achieve their full potential. Although, for these requirements to be met in a sustainable way, the planning, researching and surveillance of potential areas for expanding irrigation should be seen as primary step. It is well known that some locations already have their maize crops near full potential due environmental limitations, thus bringing unnecessary over utilization of water resources. By the other hand, there are places with plenty of potential to be explored and natural resources available, but the lack of incentives for increasing irrigation capacity, politicly and technically, make it harder to achieve the estimations of yield potential outside the computational models.

Considering projections of future environmental changes and limited space for crops, the trade-off between increased production and irrigated area expansion should be planned, prioritizing areas where water scarcity can be a major issue. Expanding towards rainfed areas from other crops (such as soybean) should be considered only with the implementation of water efficiency traits, otherwise, poor regions with fewer water resources will not achieve relevant increases on yields expected to close gaps.

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SUPPLEMENTARY MATERIAL

Table S 1. Description of the simulation parameters set for the selected Homogeneous Climate Zones (CZ), by the location (Municipality-State) of representative weather stations. Additionally, for each CZ there is a subdivision by soil characteristics of Top and SubSoil, also information regarding soil drainage (Drng), bulk density (BulkD), chosen sowing date (PltD) based on CONAB (2021). Information of area plant population (PltPop), tillage cover (Cover), terrain slope and soil depth (Soil.Z) was defined by the protocol approached by GYGA project for maize in Brazil.

Longitude	Latitude	CZ	Municipality-State	SoilTypeCover(%)	TopSoil	SubSoil	Drng	BulkD	PltD	PltPop(x1000)	Cover	Slope(%)	Soil.Z(cm)
-55,70	-22,03	1	PONTA PORÃ-MS	34,40	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-55,70	-22,03	1	PONTA PORÃ-MS	16,31	sandy clay loam	sandy loam	Excessive	1,43	01/02	55	80	2	80
-45,97	-17,53	2	JOÃO PINHEIRO-MG	41,41	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-45,97	-17,53	2	JOÃO PINHEIRO-MG	22,10	sandy clay loam	sandy loam	Excessive	1,43	01/02	55	80	2	80
-45,97	-17,53	2	JOÃO PINHEIRO-MG	10,61	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-45,41	-16,36	3	SÃO ROMÃO-MG	50,05	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-45,41	-16,36	3	SÃO ROMÃO-MG	19,74	sandy loam	loamy sand	Excessive	1,48	01/02	55	80	2	80
-45,41	-16,36	3	SÃO ROMÃO-MG	10,95	silty clay	silty clay	Poor	1,28	01/02	55	80	2	80
-45,41	-16,36	3	SÃO ROMÃO-MG	10,01	sandy clay loam	sandy loam	Excessive	1,43	01/02	55	80	2	80
-48,56	-23,71	4	BURI-SP	32,11	sandy clay loam	sandy loam	Excessive	1,28	01/03	55	80	2	80
-48,56	-23,71	4	BURI-SP	19,31	sandy clay loam	sandy loam	Excessive	1,43	01/03	55	80	2	80
-48,56	-23,71	4	BURI-SP	13,90	sandy clay loam	sandy loam	Excessive	1,43	01/03	55	80	2	80
-48,56	-23,71	4	BURI-SP	11,52	silty clay	silty clay	Poor	1,28	01/03	55	80	2	80
-48,56	-23,71	4	BURI-SP	10,96	clay	clay	Poor	1,205	01/03	55	80	2	80
-48,78	-23,93	5	ITAPEVA-SP	46,17	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-48,78	-23,93	5	ITAPEVA-SP	16,70	clay	clay	Poor	1,205	01/02	55	80	2	80

-48,78	-23,93	5	ITAPEVA-SP	15,61	clay	clay	Poor	1,205	01/02	55	80	2	80
-47,51	-16,73	6	CRISTALINA-GO	41,48	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-47,51	-16,73	6	CRISTALINA-GO	27,11	sandy clay loam	sandy loam	Excessive	1,43	01/02	55	80	2	80
-54,58	-2,70	7	SANTARÉM-PA	64,59	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-58,00	-12,26	8	BRASNORTE-MT	58,50	clay	clay	Poor	1,205	01/02	55	80	2	80
-58,00	-12,26	8	BRASNORTE-MT	13,65	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-58,00	-12,26	8	BRASNORTE-MT	10,99	sandy loam	loamy sand	Excessive	1,48	01/02	55	80	2	80
-52,53	-12,34	9	QUERÊNCIA-MT	29,35	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-52,53	-12,34	9	QUERÊNCIA-MT	23,02	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-52,53	-12,34	9	QUERÊNCIA-MT	13,34	sandy loam	loamy sand	Excessive	1,48	01/02	55	80	2	80
-55,68	-12,70	10	SORRISO-MT	35,38	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-55,68	-12,70	10	SORRISO-MT	20,06	clay	clay	Poor	1,205	01/02	55	80	2	80
-55,68	-12,70	10	SORRISO-MT	15,66	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-55,68	-12,70	10	SORRISO-MT	12,67	sandy loam	loamy sand	Excessive	1,48	01/02	55	80	2	80
-46,84	-8,22	11	CAMPOS LINDOS-TO	21,12	clay	clay	Poor	1,205	01/02	55	80	2	80
-46,84	-8,22	11	CAMPOS LINDOS-TO	16,04	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-46,84	-8,22	11	CAMPOS LINDOS-TO	15,91	clay	clay	Poor	1,38	01/02	55	80	2	80
-46,11	-9,54	12	ALTO PARNAÍBA-MA	33,94	silty clay	silty clay	Poor	1,28	01/03	30	80	2	80
-46,11	-9,54	12	ALTO PARNAÍBA-MA	33,04	sandy loam	loamy sand	Excessive	1,48	01/03	30	80	2	80
-46,11	-9,54	12	ALTO PARNAÍBA-MA	33,00	sandy clay loam	sandy loam	Excessive	1,28	01/03	30	80	2	80
-46,53	-8,49	13	BALSAS-MA	28,99	sandy clay loam	sandy loam	Excessive	1,28	01/03	30	80	2	80
-46,53	-8,49	13	BALSAS-MA	16,81	sandy clay loam	sandy loam	Excessive	1,28	01/03	30	80	2	80
-46,53	-8,49	13	BALSAS-MA	14,22	clay	clay	Poor	1,38	01/03	30	80	2	80
-46,53	-8,49	13	BALSAS-MA	12,24	silty clay	silty clay	Poor	1,28	01/03	30	80	2	80

-46,53	-8,49	13	BALSAS-MA	10,70	clay	clay	Poor	1,205	01/03	30	80	2	80
-45,84	-8,28	14	TASSO FRAGOSO-MA	36,57	silty clay	silty clay	Poor	1,28	01/03	30	80	2	80
-45,84	-8,28	14	TASSO FRAGOSO-MA	34,32	sandy clay loam	sandy loam	Excessive	1,28	01/03	30	80	2	80
-45,84	-8,28	14	TASSO FRAGOSO-MA	16,62	clay	clay	Poor	1,38	01/03	30	80	2	80
-44,75	-9,12	15	BOM JESUS-PI	66,81	sandy clay loam	sandy loam	Excessive	1,28	01/03	30	80	2	80
-44,75	-9,12	15	BOM JESUS-PI	28,00	silty clay	silty clay	Poor	1,28	01/03	30	80	2	80
-45,48	-8,13	16	RIBEIRO GONÇALVES-PI	60,15	sandy clay loam	sandy loam	Excessive	1,28	01/03	30	80	2	80
-45,48	-8,13	16	RIBEIRO GONÇALVES-PI	29,86	silty clay	silty clay	Poor	1,28	01/03	30	80	2	80
-43,98	-7,50	17	SEBASTIÃO LEAL-PI	56,37	sandy clay loam	sandy loam	Excessive	1,28	01/03	30	80	2	80
-43,98	-7,50	17	SEBASTIÃO LEAL-PI	28,91	silty clay	silty clay	Poor	1,28	01/03	30	80	2	80
-43,98	-7,50	17	SEBASTIÃO LEAL-PI	14,64	clay	clay	Poor	1,205	01/03	30	80	2	80
-45,41	-11,89	18	BARREIRAS-BA	80,29	sandy clay loam	sandy loam	Excessive	1,28	01/04	30	80	2	80
-51,01	-17,69	19	RIO VERDE-GO	40,83	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-51,01	-17,69	19	RIO VERDE-GO	22,50	sandy loam	loamy sand	Excessive	1,48	01/02	55	80	2	80
-52,80	-24,59	20	CAMPINA DA LAGOA-PR	59,02	clay	clay	Poor	1,205	01/02	55	80	2	80
-53,24	-24,72	21	CORBÉLIA-PR	26,17	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-53,24	-24,72	21	CORBÉLIA-PR	17,02	silty clay	silty clay	Poor	1,28	01/02	55	80	2	80
-53,24	-24,72	21	CORBÉLIA-PR	15,73	sandy clay loam	sandy loam	Excessive	1,28	01/02	55	80	2	80
-53,24	-24,72	21	CORBÉLIA-PR	15,08	sandy clay loam	sandy loam	Excessive	1,43	01/02	55	80	2	80
-53,24	-24,72	21	CORBÉLIA-PR	10,81	clay	clay	Poor	1,265	01/02	55	80	2	80
-60,60	-13,53	22	CABIXI-RO	21,35	sandy clay loam	sandy loam	Excessive	1,28	01/04	55	80	2	80
-60,60	-13,53	22	CABIXI-RO	20,12	clay	clay	Poor	1,38	01/04	55	80	2	80
-60,60	-13,53	22	CABIXI-RO	18,67	clay	clay	Poor	1,38	01/04	55	80	2	80
-60,60	-13,53	22	CABIXI-RO	10,25	sandy clay loam	sandy loam	Excessive	1,28	01/04	55	80	2	80

-61,59	-13,10	23	PIMENTEIRAS DO OESTE-RO	27,28	sandy clay loam	sandy loam	Excessive	1,28	01/04	55	80	2	80
-61,59	-13,10	23	PIMENTEIRAS DO OESTE-RO	23,65	clay	clay	Poor	1,38	01/04	55	80	2	80
-61,59	-13,10	23	PIMENTEIRAS DO OESTE-RO	22,85	sandy clay loam	sandy loam	Excessive	1,28	01/04	55	80	2	80
-61,59	-13,10	23	PIMENTEIRAS DO OESTE-RO	10,46	clay	clay	Poor	1,38	01/04	55	80	2	80