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ARTICLE

Potential impacts of reducing the microregional yield gaps for main food crops in Brazil

Impactos potenciais da redução do hiato de rendimento microrregional das principais culturas alimentares no Brasil

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Abstract: This study aimed to measure yield gaps and the potential gains in production and revenue from mitigating these gaps for the four main food crops in Brazil and worldwide (rice, maize, soybean, and wheat). Based on the concepts of potential yield, observed yield, and yield gap, and data from the 2017 Brazilian Agricultural Census, a parameter for the potential yield of each crop was defined at the microregional level, and yield gaps and potential gains in production and revenue resulting from reducing these gaps were measured. The results showed that reducing yield gaps in Brazil for the analyzed crops may lead to an expansion in supply of these food products by almost 10% of the volume achieved in 2017, or the equivalent of 19 million tons. The greatest potential gains in yield and production were found for maize, 13.2%, valued at about US$ 1.7 billion (at 2017 prices). Soybean showed the lowest potential for gains in percentage terms (5.5%), but these gains would represent US$ 1.8 billion, the highest value among the crops analyzed.

Keywords: food security, yield gap, food crops in Brazil.

Resumo: Este estudo teve como objetivo mensurar os hiatos de rendimento e os ganhos potenciais de produção e receita advindos da redução desses hiatos para as quatro principais culturas alimentares do Brasil e do mundo (arroz, milho, soja e trigo). Baseado nos conceitos de rendimento potencial, rendimento observado e hiato de rendimento, e em dados do Censo Agropecuário Brasileiro de 2017, definiu-se um parâmetro para o rendimento potencial de cada cultura, em nível microrregional, e mensuraram-se os hiatos de rendimento e os ganhos potenciais de produção e receita decorrentes da redução desses hiatos. Os resultados revelaram que a redução dos hiatos de rendimento no Brasil para as culturas analisadas pode permitir a ampliação da oferta dessas culturas alimentares em quase 10% do volume registrado em 2017, ou 19 milhões de toneladas. Para o milho foram encontrados os maiores ganhos potenciais em rendimento e produção, 13,2%, valorados em cerca de R$ 5,5 bilhões (a preços de 2017). Já para a soja, identificou-se o menor potencial de ganhos em termos percentuais (5,5%), mas que representariam R$ 5,7 bilhões, o maior valor entre as culturas analisadas.

Palavras-chave: segurança alimentar, hiato de rendimento, culturas alimentares no Brasil.

1 Introduction

Food security has been widely recognized as one of humanity's greatest challenges. However, since the 2007/2008 commodity crisis, interest in this topic has intensified worldwide (Cole et al., 2018; Sassi, 2018; Nóia Júnior & Sentelhas, 2020). According to FAO, IFAD, UNICEF, WFP and WHO (Food and Agriculture Organization of the United Nations, 2019), over 800 million people around the world (approximately one in nine) still suffer from hunger.

The challenge of ensuring food security becomes even more important when considering the long-term perspective. Projections of world demographic expansion show about 9.73 billion people in the world by 2050, representing a 35.1% increase compared to 2015. This expansion, along with projected growth in income and urbanization, scarcity of natural resources, environmental constraints, and climate change, amplifies the challenge of ensuring sustainable and accessible food supply in the future. FAO estimates that to cope with the projected increase in demand, agricultural production will need to increase by almost 50% by 2050 compared to 2012 levels (Food and Agriculture Organization of the United Nations, 2017).

In the past, the world's demand for food was met by expanding cultivation areas and increasing productivity, the latter being the main driver of growth from the 1960s onwards (Godfray et al., 2010). According to FAO data, 86% of the expansion of global agricultural production from 1961-2007 was due to yield gains (77%) or an increase in cultivation intensity (9%), while only 14% due to area expansion (Alexandratos & Bruinsma, 2012). However, in recent years, cultivation area expansion has been quite limited and productivity gains have shown signs of deceleration in major crops worldwide, leading some observers to question the role of productivity gains in the coming decades (Hertel & Baldos, 2016).

Faced with the need to expand food supply, and considering the limitations of resources and current environmental and climate constraints, reducing the yield gap – i.e. the difference between the potential yield of agricultural crops under optimal conditions and those actually obtained by producers – has emerged among potential strategies. The size of this yield gap can be understood as a proxy for unexplored agricultural production capacity, according to Lobell et al. (2009).

In recent years there has been a rapid growth of research interest in the yield gap in agricultural crops, with numerous research studies emerging, such as (Lobell et al., 2009; Licker et al., 2010; Langeveld et al., 2014; Merlos et al., 2015; Sentelhas et al., 2015; Andrea et al., 2018; Battisti et al., 2018; Dias & Sentelhas, 2018; Nóia Júnior & Sentelhas, 2020; Liu et al., 2021) among others. However, almost all of these studies have focused on agronomic aspects. Topics such as the measurement of the potential for expansion in agricultural production, as well as revenue resulting from yield gap reduction have been neglected by almost all of them. Sentelhas et al. (2016) support this finding by highlighting that this theme is among the main lines of research current in various agronomic knowledge areas. Nevertheless, it is still very underexplored in other areas, such as economic and related fields.

Thus, this study intends to explore this theme from an economic perspective, aiming to measure the yield gap of rice, maize, soybean, and wheat crops in Brazil, as well as the potential for expansion of production, and of agricultural revenue by reducing these gaps without the using new land areas. The analysis uses the last Agricultural Census data available for Brazil, from 2017. The study explicitly considers the regional heterogeneity of Brazilian agriculture by adopting the country's 5,570 municipalities and 558 geographical microregions as units of analysis. This aspect is particularly relevant for this kind of study, as Andrea et al. (2018) state, both yield levels and yield gaps are strongly influenced by climatic elements, which vary spatially.

This paper contains five sections, including this introduction. The second section discusses concepts of productivity, yield gap and their determinants, and systematizes a brief review of the empirical literature on the subject. The third presents the methodology. In the fourth section, results are presented and discussed, comparing them, when possible and pertinent, with the results of other studies. The fifth section presents the conclusions.

2 Theoretical and Empirical Approach

2.1 Defining and measuring yield gap

The difference between the term's productivity and yield in the literature on agricultural activity is not always clear. Dawe & Dobermann (1999), arguing that these terms were sometimes used inconsistently by agronomists and economists, sought to define them more carefully. According to the researchers, the term agricultural productivity is related to the use of production factors (labor, machinery, fertilizers, pesticides etc.), while the term agricultural yield is used to associate the product and the land area used in production, corresponding to the ratio of product per hectare. The term yield gap derives from the term yield.

Fischer (2015), in an attempt to systematize concepts related to the terms agricultural yield and yield gap, defines agricultural yield as the weight of grain (or other product) per unit of cultivated area, usually measured in metric tons per hectare. The term yield gap refers to the difference between the potential yield (the maximum possible under certain conditions) of a crop and the actual yield obtained on farms.

According to Lobell et al. (2009), potential yield is the yield of an adapted or hybrid variety that grows without the limiting biophysical conditions of water, nutrients, pests or diseases. For a given local and temporal condition, this potential yield would be determined by factors such as solar radiation, temperature, and water supply, which change throughout the plant's growth cycle. Plant genetics and even density can alter this potential. For these authors, achieving potential yield requires almost perfect management of factors linked to the soil and plant growth cycles. They argue that it might be possible for some producers to get close to their potential, but this is neither feasible nor profitable for most of them. Fischer (2015) emphasizes that the essential conditions to reach a potential yield include the best adaptable variety, the best agronomic and input management and the absence of abiotic and biotic stresses.

There are four ways recommended by the literature to measure potential yield for an agricultural crop or a proxy for it [see for example Lobell et al. (2009); Fischer (2015); Sentelhas et al. (2015); Battisti et al. (2018)]: 1) crop simulation model (a single model or several models); 2) field experiment; 3) yield contest; 4) maximum yield obtained by farmers. Each of these has advantages and disadvantages, which are widely discussed in the literature.

Sentelhas et al. (2015) and Sentelhas et al. (2016), based on several concepts of agricultural yield presented by other authors, distinguish six types of yield and resulting yield gaps: potential (or theoretical) yield, optimal irrigated yield, average irrigated yield, attainable yield, optimal actual yield under rainfed conditions and average actual yield under rainfed conditions. From these concepts emerge different yield gaps, defined as the difference among types of yield for a specific crop condition. For these authors, several factors may explain the differences among types of yield, and among different producers and regions, with emphasis on biophysical and socioeconomic factors. Biophysical factors include nutrient deficiency, hydric stress, soil quality, insect losses, diseases, climate problems and seed quality etc. These can also be defined as determining, limiting, and reducing. The first two are associated with the climate and its variability and can be managed through an appropriate choice of location and sowing season. Reducing factors are associated with management and agricultural practice, including soil preparation, correction and management and phytosanitary control. Socioeconomic factors, on the other hand, include producer risk aversion, capacity credit taking and available time and knowledge to explore potentialities. Figure 1 represents some of these concepts and determinants.

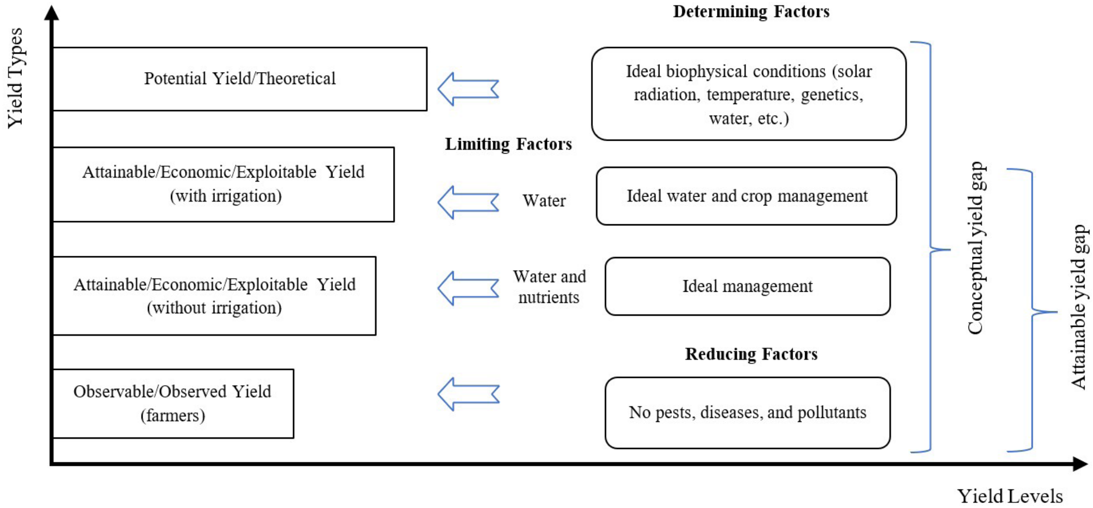

Figure 1. Agricultural yield levels and their respective determining factors.
Source: adapted from Sentelhas et al. (2016).

The next section reviews a set of studies that sought to measure the yield gap for different crops, under different spatial scales (global and local), using different methods.

2.2 Brief review of the empirical literature

Many studies on yield gap seek to relate the issue to food security under the hypothesis that reducing or closing it is an important strategy to increasing agricultural supply and meet projected expansion of future food demand without the need to expand cultivated areas. These studies typically aim to quantify the yield gap, identify its causes, and recommend possible solutions for its mitigation. This section reviews the main studies that fall within this scope, published between 2009 and 2020.

Lobell et al. (2009) provide an overview of different definitions and methods for estimating yield gaps. They analyzed evidence on the magnitude and causes of yield gaps for different rice, wheat, and maize cropping systems in major producing regions around the world. Average yield levels for crops and regions found by researchers ranged from 20% to 80% of the potential yield.

Licker et al. (2010) analyzed the determinants of yield gap for 18 agricultural crops around the globe, which together represented 85% of the entire area used for agriculture in the world. National and regional agricultural census and satellite databases were used for the different countries for the years 1997 to 2003. The authors used the 90th percentile of observed yields for each crop in each climate zone as the reference yield – referred to as 'climatic' potential yield – for measuring the yield gaps. The results showed that, in most cases, developed countries had smaller yield gaps. They also found that it would be possible to increase global maize production by approximately 50%, rice by around 40%, soybean by 20% and wheat by 60% if 95% of the main producing regions reached the reference yield ('climatic' potential yield).

Ittersum et al. (2013) presents concepts and reviews different methods of analyzing the agricultural yield gap, addressing the implications of using these methods and the relevance (consistency) of the results produced at global and local (national or subnational) scales. They concluded that global studies are fraught with methodological assumptions and data uncertainties that prevent them from being reliable sources for estimating yield gaps at the local level. They advocated for a protocol to estimate yield gaps with local-to-global relevance, maximizing the use of local knowledge and data in order to produce locally consistent results.

Merlos et al. (2015) analyzed yield gaps and the potential for increased agricultural production in Argentina. Yield gaps were estimated for soybean, wheat, and maize, and the amount of additional production that could be achieved by the country by eliminating these yield gaps for these crops was calculated. Potential and water-limited yields were estimated based on different crop simulation models, and actual (observed) average yields of producers were obtained from data from the Ministry of Agriculture of Argentina and upscaling of studies from the Global Yield Gap Atlas (GYGA). The national yield gap represented 41% of the water-limited potential yield for wheat and maize, and 32% for soybean. It was found that if these yield gaps were reduced to 20% of the potential yield, Argentina could increase its production of soybean, wheat, and maize by 7.4, 5.2, and 9.2 million tons, respectively, without expanding its cultivated area.

Sentelhas et al. (2015) estimated the magnitudes of yield gaps and their determinants for soybean cultivation in 15 locations across 13 Brazilian states. Potential and attainable yields were simulated in each location and yield gaps (limited by water, suboptimal management, and total) were estimated. The actual average yields (observed) for producers in each region were calculated from national surveys for the period 1980-2011, obtained from official Brazilian agencies. It was identified that the main cause of yield gap for soybean in Brazil during the period was water deficit, followed by suboptimal farm management. The authors concluded that soybean production in Brazil could be increased substantially by reducing the yield gaps and raising the current yields of producers through different strategies.

In another study on soybean in Brazil, Battisti et al. (2018) quantified yield gaps caused by water deficit and suboptimal management in areas of yield contests monitored by the Brazil Soybean Strategic Committee (CESB). Potential and attainable yields were estimated using a crop simulation model, and actual yields were obtained from a sample of 200 farms, extracted from the universe of participants in yield contests in the 2014/2015, 2015/2016, and 2016/2017 crop seasons. For the authors, considering 80% of the average yield of the winners of those contests as a reference yield, there is a gap for, in the near future, doubling the current yield of soybean in Brazil by adopting the technology already available, without the need to expand the area.

Dias & Sentelhas (2018) investigated the sugarcane yield gap in Brazil, its magnitude and causes using a multi-model crop simulation approach. They estimated the potential yields and water-limited yields for sugarcane in 30 locations across 12 Brazilian states. Actual yields were obtained from IBGE national surveys for the period 1994-2013 and varied substantially across locations, depending on climate, soil, and management conditions. The authors found that reducing the yield gap caused by suboptimal management by 20% to 100% would result in a decrease in sugarcane area by 9% to 32%.

Andrea et al. (2018) analyzed the yield gaps of rainfed maize in six locations in Brazil's Central-Southern region in the first and second growing seasons, along with their primary causes, as well as yield and gap variability. Potential and water-limited yields were estimated using a crop simulation model. Gaps due to management were greater than those resulting from water deficit in both growing seasons. Crop management constraints proved to be more limiting than water in regional gaps for maize in almost all scenarios. The authors show that improvements in management have potential to increase yields and national maize production without requiring new areas.

Nóia Júnior & Sentelhas (2020) was the only identified study on the yield gap in Brazil that also attempts to investigate the impact of reducing the gap on producers' revenues. The authors sought to determine the magnitude of the yield gap and revenue loss caused by water deficit and suboptimal management of the double-crop system of main-season soybean with off-season maize in different Brazilian regions. Three crop simulation models were used to estimate potential and water-limited yields for 28 locations in 12 Brazilian states over the period 1980-2013.

Average yields of producers were obtained from the IBGE for the period 2003-2017. Revenue loss was estimated by multiplying the yield gaps for soybean and maize by their respective sales prices, using the 5-year averages (2013-2017) of these prices. Overall, for soybean, suboptimal management was slightly more often the main cause of the total yield gap, while for maize, the water deficit was slightly more relevant. Revenue losses for the crop succession system (double-crop system) due to water deficit were between US$ 181 and US$ 1,822 ha^{-1}. As for the loss of revenue caused by suboptimal management, the national average was US$ 734 ha^{-1}, of which 46.3% was for soybean crops.

Among all the studies revised in this section, both on a global and local scale (national and subnational), only two – Licker et al. (2010) and Nóia Júnior & Sentelhas (2020) – tried to quantify the potential increase in production resulting from the yield gap reduction, and only Nóia Júnior & Sentelhas (2020) estimated the potential impact of the yield gap reduction on farmers' revenue. This reinforces the value of carrying out the present study and the methodological strategy used.

3 Methodology

The yield gap, as addressed in previous sections, can be understood as the difference between potential yield and the yield obtained by the producer in a given period. In order to measure the yield gap of the four main agricultural crops in Brazil and the potential for production and revenue expansion for farmers through the reduction of these gaps in the present study data from the Brazilian Agricultural Census of 2017 (Instituto Brasileiro de Geografia e Estatística, 2020a) were used. The basic unit of reference for agricultural establishments in the study is the municipality, and production and harvested area data for each of the 5,570 Brazilian municipalities were used to obtain municipal and microregional yield numbers. Data from the Municipal Agricultural Production (Instituto Brasileiro de Geografia e Estatística, 2020b) were used to analyze the observed yield behavior of the four crops between 1978 and 2017.

To measure the yield gap in 2017, the average of agricultural establishments in each municipality was used, which is the available information. For potential yield (attainable potential in this case), the average of the yield of establishments of the 4th quantile group was used in each microregional unit – 558 in Brazil. According to the IBGE, a geographic microregion is defined as a geographic area composed of a set of bordering municipalities with similarities in production and articulation with larger spaces, as well as social and geographic characteristics, although this does not mean uniformity in these attributes. As it maintains similar socioeconomic and climatic conditions among its municipalities, the microregion was adopted as a geographic reference space for calculating the potential yield in this study, thus allowing inferences about the reasons for any observed differences in yield.

As mentioned, there are several methods for determining potential yield, including crop simulation models, agronomic experiments under controlled conditions which use a maximum obtained in a specific sample, yield competitions between producers, and maximum yield obtained among producers. As noted by Lobell et al. (2009), although this last option, used as a proxy for potential yield, does not consider ideal conditions, it can be a good approximation of theoretical potential yield. Some studies attempt to separate groups of producers through similar climatic conditions (Licker et al., 2010) and other nearby natural ecosystems.

The use, in this study, of the average of the 4th quantile group as a parameter of potential yield, allows representation of similar and feasible productive conditions among the highest yielding producers. This indicator is adopted in this study as a parameter for the potential product, without climatic, hydric and cultural limitations, among others, being obstacles.

Licker et al. (2010) used the 90th percentile of observed yields for each crop in each climatic zone as a reference potential yield. In the present study, calculations were also performed using the 90th percentile for comparison purposes. However, the results generated were very similar to those obtained using the average of the 4th quantile group.

Based on the potential yield calculated for each microregion, the yield gaps were measured in each producing area for producers with yields lower or equal to that parameter (the calculated potential yield). For producers whose observed yields were higher than the microregional parameter, their yields were maintained. The average municipal prices of each crop were calculated based on the value of production and the volume produced. All procedures were performed in the R software.

It was not possible to identify whether the highest yields obtained in each microregion include the ideal management and irrigation conditions, according to parameters discussed in the literature review. Thus, it is not possible to assert that the highest yields in certain crops and regions were obtained with the use of irrigated systems, since the information available from the 2017 Agricultural Census does not allow such inferences to be made. However, it is verified that the use of irrigated systems is present in all microregions considered.

Due to the methodology adopted in this study, the reduction of the yield gap for each crop occurs in a generalized way within all Brazilian microregions, homogenizing their yields based on the highest levels, but still preserving the differences among the different microregions of the country. Given the diverse climatic systems present in Brazil due to its territorial dimensions, the use of microregions as an area of comparison for yields by crop allows for an approximation of cultural, socioeconomic, and climatic realities, while still managing the differences in yields through producer and/or public policy actions.

4 Results and Discussion

4.1 Brief considerations about the most important crops in Brazil

The analysis involves the main food crops in Brazil and worldwide, rice, maize, soybean, and wheat. In 2017, these four crops occupied approximately 70% of harvested areas and represented 55% of the value of crop production in Brazil, according to IBGE (Instituto Brasileiro de Geografia e Estatística, 2020a). Furthermore, their production volumes represented about 1.62% of global rice production, 8.41% of maize production, 32.5% of soybean and 0.56% of wheat production in 2017, according to FAO (Food and Agriculture Organization of the United Nations, 2020). Rice and wheat produced in Brazil are essentially for national human consumption and are in the daily diet of most Brazilians. Maize and soybean are mainly inputs for local agroindustries, are exported and are used for human and animal consumption. In addition to the current importance of this group of products for human and animal nutrition in Brazilian territory, they will gain even more relevance in coming decades, with the growth of world population and income, and therefore a greater consumption of cereals and meats.

Rice is the third most consumed cereal in the world and is grown in many parts of the planet, especially in regions with high social vulnerability such as Africa, Asia, and Latin America; it is also an integral part of the almost daily eating habits of Brazilians. In Brazil, this cereal is grown in almost the entire territory, in about 180 thousand agricultural establishments, and in 2017 in total 11 million tons were produced. Rice exports and imports represent around 10% of supply, keeping national production close to demand. Different cultivation systems are used: floodplain ecosystems (irrigated/flooded), in which the rice is submerged under water, while in highlands supplementary sprinkler irrigation or rainfed systems are used.

Rice production when rainfed is dependent on the rainfall regime, and water stress during the cycle can compromise crop yield. In Brazil, there is a wide variety of types of rice, including white rice (long, medium, short grain), brown or wholegrain, basmati, red, and black arboreal, but white rice represents more than 70% of national consumption (Companhia Nacional de Abastecimento, 2015).

Maize is one of the main cereals for human and animal consumption, as well as being used as a raw material in the production of starches, oils, alcoholic beverages, food sweeteners and fuels. In Brazil, this cereal is the second main agricultural product in cultivated area, occupying about 16 million hectares and volume of 88 million tons in 2017, only behind soybean. Over the last five decades, Brazil has increased its production volume, supported especially by accelerated yield gains. The average yield has more than tripled in recent decades, while cultivated areas have not significantly changed. The country has recently expanded its presence in the international maize market, becoming the second largest exporter, behind the United States. Among factors contributing to this expansion are new varieties, expansion of production in regions of higher productivity, climatic capacity to produce two growing seasons per year and government support. Investments in port infrastructure have also contributed to the exportation of surpluses.

As a traditional crop with a diversity of uses, maize production was cultivated in around 1.6 million establishments and occupied 21.9% of the harvested area of crops throughout Brazil in 2017. The Center-West region has been gaining ground in national production being cultivated in large properties and with higher yields. With 2.5% of the country's farms and 53% of the harvested area, the Center-West region produced 55% of the national production in 2017. Municipal Agricultural Production data (Instituto Brasileiro de Geografia e Estatística, 2020b) shows that production has rapidly expanded in this region since the 2000s, while in the others the trend has been for a reduction in area. It is worth noting that yield gains accelerated from the 2000s in all regions of the country.

Soybean is Brazil's main agricultural product in terms of cultivated area. The country produced around 103 million tons of the grain in 2017, which was its largest harvest ever recorded in terms of volume and average yield. There were about 236 thousand establishments producing soybean in the country, covering 30.7 million hectares. Soybean has been the commodity with the greatest expansion in volume in Brazil in recent decades, among the four crops under analysis, especially due to the growth of area (in 2017 it occupied about 43% of the crop areas), since the growth of the yield was below that of other crops, although it has also contributed to the expansion of national production. High economic attractiveness and greater liquidity have guaranteed its growth throughout the national territory, overtaking other traditional crops such as maize and rice, and taking over pasture areas. According to Hirakuri & Lazzarotto (2014), the success of soybean in Brazil derives, in addition to high international demand and attractive relative prices, from an effort to transfer technology, knowledge and management techniques that have brought good results in all producing regions.

The fourth product analyzed in this study is wheat, one of the oldest cereals and a main foodstuff today. Although there are about 30 types of wheat, three species represent more than 90% of national production volume. Its production in Brazil extends from the Southern region to the Brazilian cerrado (Brazilian savanna). However, it is especially present in the Southern region, with about 90% of national volume being produced there, mainly through rainfed cultivation, with a yield around 2.6 tons per hectare (t ha^{-1}). As a winter crop, the activity initially expanded in the Southern region, but due to technological advances (genetic improvements and wide edaphoclimatic adaptation), production has been gaining ground in other regions of the country (Companhia Nacional de Abastecimento, 2017).

In the 1990s, trade liberalization and intensification of trade among Mercosur countries resulted in an increasing volume of wheat imported by Brazil at very competitive prices, which reduced the profitability of the domestic product and increased production risks, leading many national producers to leave the activity. There was a trend towards declining area and production volume in Brazil, partially reversed in the 2000s, but the current area is still smaller than that explored in the 1980s. On the other hand, production volume in the country has been growing in the last two decades due to the high yield gains. According to Embrapa (Empresa Brasileira de Pesquisa Agropecuária, 2018), the number of cultivars has grown significantly since the late 1990s. Currently, Brazil continues to be a net importer of wheat and its derivatives, with local supply meeting about 50% of national demand, with imports mainly from Argentina and the United States. With the support of state and private research centers, genetic development of new seed varieties adapted to local conditions has increased the productive potential, allowing yields above four tons per hectare.

4.2 Potential gains eliminating microregional yield gap in Brazil

Based on the average municipal yield data by crop in the year 2017 as an observed yield parameter and the average of the highest microregional yields in that same year, yield gaps of each crop in each municipality were calculated. Aggregated results by crop in the five major Brazilian regions are presented in Table 1. Columns 2, 3 and 4 show yield data and estimated microregional yield gaps. Columns 5, 6 and 7 show production volumes and potential growth considering the closing of microregional yield gaps. Column 8 presents monetary gains generated by the closing of the yield gaps, considering the average prices of products in the base year (2017). The ninth and last column shows the values related to potential cultivated area savings resulting from yield gains, calculated under the assumption of maintaining the production volume at 2017 levels, but with yields equivalent to the potentials.

Considering the constraints on expanding agricultural areas for food production in Brazil and the rest of the world, gains in yields through reducing yield gaps not only increase food supply, but also reduce the demand for new areas, thereby contributing to environmental preservation and mitigating global warming.

For rice, considering the reduction of the microregional gap in Brazil, yield and volume gains were estimated at 8.8% over 2017 values. This represents an increase in average yield, from the current 6.4 t ha^{-1} to 7.1 t ha^{-1}, and allows for the expansion of production by almost 1.0 million tons of product, which is equivalent to US$ 245.2 million at 2017 prices. Achieving these gains required investments in technology and labor by some farmers, as well as a significant effort by governments to sponsor an approach between regional yields.

Given the wide variety of rice existing in some Brazilian microregions, reducing the yield gap would also imply greater regional specialization and scale gains in specific varieties. However, this does not require the yield and variety differences between microregions to be nullified, since the unit of reference is the microregion. In addition to the highlighted benefits and costs, it should be noted that given rice consumption of approximately 51 kg per capita per year (11.2 million tons and 220 million inhabitants) in Brazil, the volume gains resulting solely from closing the yield gap measured in this study could serve 19 million new consumers, about 9% of the national population. This conjecture helps to assess the importance of reducing the yield gap in rice supply in Brazil.

Table 1. Measuring microregional yield gaps for rice, maize, soybean, and wheat and gains obtained with closing these gaps in Brazil

Crops and Regions	Average yield in 2017 (t ha-1)	Potential yield (t ha-1)	Yield gap (t ha-1)	Volume in 2017 (1000 t)	Potential volume (1000 t)	Potential volume (%)	Value change (US$ million)	Saving land (1000 ha)
Rice	**6.44**	**7.01**	**0.57**	**11,056.7**	**12,030.0**	**8.8**	**245.2**	**133.5**
N*	1.90	2.54	0.64	255.3	341.2	33.8	31.0	34.2
NE	4.26	4.79	0.53	743.8	836.3	12.4	26.2	21.1
S	7.66	8.23	0.57	9,422.7	10,120.3	7.4	167.9	84.4
SE	4.36	4.89	0.53	39.7	44.8	12.1	1.5	0.9
CO	3.54	4.08	0.54	595.3	684.8	15.1	19.2	20.2
Maize	**5.58**	**6.32**	**0.74**	**88,099.6**	**99,729.2**	**13.2**	**1,723.5**	**1,837.6**
N	3.35	4.05	0.70	5,529.5	6,679.0	20.8	280.0	283.9
NE	3.72	4.38	0.66	2,020.9	2,380.7	17.8	80.6	81.6
S	6.08	7.00	0.92	22,417.7	25,803.1	15.1	520.7	483.6
SE	6.17	7.32	1.15	9,556.9	11,344.2	18.7	316.0	243.4
CO	5.81	6.40	0.59	48,574.7	53,529.7	10.2	526.2	769.8
Soybean	**3.35**	**3.54**	**0.19**	**103,156.3**	**108,829.6**	**5.5**	**1,788.3**	**1,563.3**
N	3.08	3.23	0.15	8,877.6	9,304.1	4.8	139.2	128.9
NE	3.02	3.27	0.25	4,088.0	4,427.3	8.3	107.2	102.8
S	3.45	3.67	0.22	34,473.4	36,679.3	6.4	720.0	603.5
SE	3.47	3.73	0.26	7,428.5	7,986.2	7.5	187.1	146.0
CO	3.37	3.51	0.14	48,288.8	50,365.4	4.3	635.8	590.4
Wheat	**2.62**	**3.07**	**0.45**	**4,681.1**	**5,486.1**	**17.2**	**145.2**	**263.8**
N	-	-	-	-	-	-		-
NE	-	-	-	13.0(**)	-	-		-
S	2.58	3.01	0.43	4,089.8	4,764.8	16.5	118.3	224.1
SE	2.97	3.63	0.66	517.7	633.0	22.2	24.1	31.0
CO	2.25	2.83	0.58	60.6	76.7	25.8	3.2	5.5
Total to 4 crops	-	-	-	**206,993.7**	**226,037.4**	**9.2**	**3,902.1**	**3,802.6**

Source: research data based on data from IBGE (Instituto Brasileiro de Geografia e Estatística, 2020a). *N (North), NE (Northeast), S (South), SE (Southeast), CO (Midwest). **There is a small production in the Northeast region, but due to the number of producers in the municipality being less than three, the data were not made available and analyzed.

Table 1 also shows the regional data, from which can be observed the high spatial concentration of rice production in Brazil, with the South accounting for just over 85% of the national total (especially producing long-fine-grain rice). Favorable edaphoclimatic conditions and production, especially in irrigated systems (near rivers or dams) provide high yields, around 7.5 tons per hectare (with a significant portion of leased land), produced in 19.7 thousand agricultural establishments. Other regions of Brazil have reduced in the national supply in recent decades, with volume, area and yield declining. In the North, Northeast, Southeast and Center-West regions, rice cultivation is restricted, for the most part, to small rainfed areas, on small farms with basic technology, poor logistics and, often without the necessary agronomic care, resulting in low yield levels; there are approximately 160 thousand establishments. In many cases production is for subsistence.

It is important to note that in those same regions (North, Northeast, Southeast and Center-West) are technified areas with rice production, using flood irrigation and more resistant cultivars, such as production along the banks of the São Francisco River and in the Tocantins basin, which have high yields. Additionally, successful examples in the tropical region indicate the region's potential from the adoption of appropriate technologies and varieties. Among analyzed regions, the Northeast had the lowest average yield for rice in 2017, but has the highest potential percentage gain from reduction of yield gap among analyzed regions, ranging from 1.9 t ha^{-1} on average to 2.5. In the South, a reduction of the gap will represent a potential increase of 7.4%, which amounts to 697 thousand tons or about US$ 168 million. According to CONAB (Companhia Nacional de Abastecimento, 2015), fertilization of irrigated rice is one of the most important practices to achieve a high yield.

Table 1 reveals that reducing the yield gap for maize has potential for expanding the national supply of this grain by 13.2%, with gains in all Brazilian regions, totaling around 11.6 million tons or US$ 1.7 billion. This is the largest gain among the evaluated crops. These gains would be more expressive in the Northern region, which would increase from 3.4 to 4.4 t ha^{-1}. In the Center-West region, the main producing region, the increase in yield would go from 5.8 to 6.4 t ha^{-1}, representing a 10.2% increase in regional volume. The differences in yield among producers and regions are significant and have been increasing as new technologies and techniques are being applied to a select group of producers. Even in the Northeast region, which suffers from frequent periods of drought, there are producers with high yields, although the vast majority present low yields.

Andrea et al. (2018) analyzed the yield gap of rainfed maize in some localities in Brazil using a crop simulation model and historical data from 1990 to 2013. Although it is not possible to directly compare the figures, the authors emphasize that the yield gap was caused more by management than water deficit. This reinforces the importance of better crop management. In contrast, in Nóia Júnior & Sentelhas (2020), which aimed to analyze the magnitude of the yield gap and the losses caused by water deficit and suboptimal management via a simulation model, the authors found that the water deficit was slightly more relevant, with the choice of best sowing date being the central variable to reduce the water deficit for maize.

The benefits of reducing maize' yield gap in Brazil, besides presenting the highest gains in supply side among the four main food crops in the country, would lead to a wide distribution of these benefits, as they include about 1.6 million agricultural establishments. However, these gains would require further efforts by the public sector to enable investments in technology and labor in low-yield and subsistence cultivation areas. In addition to the US$ 1.7 billion that these efforts could generate for the country, reducing the gap and expanding the average crop yield could reduce the need for area by 1.8 million hectares, maintaining current production volumes. Furthermore, the increase of 11.6 million tons in production would allow reaching around 43 million new consumers (59.2 million tons of national consumption by the population of 220 million), considering the total national consumption for this grain.

For soybean, Table 1 shows that the closing of microregional yield gaps would result in a 5.5% increase in the national average yield, from the current 3.3 to 3.5 t ha^{-1}. This would represent an increase of 5.6 million tons and US$ 1.8 billion at the 2017 price. The gains in volume are not greater than in maize due to the smaller yield gap for soybean among the different producer groups and regions in the country. High yields are observed even in groups of smaller areas and in all producing regions.

The differences in soybean yield are less significant among regions when compared to other crops, as can be seen in Table 1. It occurs because soybean production has a technological package with allowing adaptation of production in different regions. The average yields among the different regions range from 3.0 and 3.5 t ha^{-1}. In terms of land economy, these yield gains would allow for a reduction of 1.5 million hectares of soybean cultivated area while maintaining the production volume achieved in 2017. In terms of regional results, Table 1 shows gains concentrated in regions where soybean cultivation is more widespread, namely the Center-West and South regions. It is worth noting that soybean cultivation has been advancing rapidly in the Brazilian agricultural frontier regions and in the degraded pasture areas of North and Northeast regions of the country, according to Hirakuri & Lazzarotto (2014).

Sentelhas et al. (2015) estimated average yield growth for soybean by closing differences between potential and actual yields using a crop simulation model. The authors identified that a large part of the yield gap for soybean comes from the water deficit (76.8%), while inadequate management represents on average only 26.2%. They emphasize the importance of adopting the best recommendations for sowing times, the use of no-tillage systems to conserve water in the soil and choosing cultivars that are more tolerant to water deficit. The use of irrigated systems for the soybean in Brazil is quite restricted and occupies a small area, according to the authors. Thus, soybean production in Brazil could be increased through different strategies, which include expansion of irrigation, the crop rotation system and precision farming.

Battisti et al. (2018) also argue that there is potential to double current Brazilian soybean yield by adopting the technology already available to farmers, without the need for area expansion. According to Embrapa (Empresa Brasileira de Pesquisa Agropecuária, 2019), proper soil management in soybean production increases the ability of plants to tolerate water deficits, as well as providing greater capacity to exploit macro and micronutrients. Control of acidity and the conservationist management of the soil and water contribute to the achievement of high fertility. Furthermore, the efficiency of fertilizer use is highly dependent on climate, phytosanitary management and phytotechnical positioning, which requires regionalized fertilization to reach high yields. The sowing time (which varies from September to December), plant population and cycle are also determining factors in the yields obtained.

Still as shown in Table 1, reduction of the microregional yield gap for wheat could increase the average yields in Brazil, to rise from 2.6 to close to 3.1 t ha^{-1}; which means a 17.2% growth in volume for the same area. Considering the 4.68 million tons produced in 2017, this would represent something around 805 thousand tons, equivalent to US$ 145.2 million generated by 35 thousand agricultural establishments. Considering the potential for human food, this is equivalent to feeding around 15.6 million new consumers (taking into account the 11.3 million tons of domestic consumption in Brazil and its 220 million inhabitants). A large portion of these gains would come from the South, which has about 90% of the cultivated area. The reduction of yield gap in this region could increase its production volume by 16.5%, which represents an increase of 674 thousand tons.

In the Southeast and Center-West regions of Brazil, where production has also been growing in recent decades, wheat is produced under rainfed and irrigated systems. In the Southeast, the second largest producing region, reduction of the estimated gap would represent even greater proportional gains, to rise from an average yield from 2.9 to 3.6 t ha^{-1}. In the Center-West region, which currently has an average yield below that of other regions and a small production volume, reduction of the microregional gap could raise average yield by 25.8%. According to CONAB (Companhia Nacional de Abastecimento, 2017), there is great expectation of an increase in wheat production in this region, but this still depends on varieties adapted to the edaphoclimatic conditions of the savanna and commercial advantages. Irrigated wheat cultivation allows breaking the cycle of diseases and pests exclusive to legumes, which helps the activity to expand in regions that produce grains such as soybean, maize, and beans.

Figure 2. shows the spatial distribution of production gains across Brazilian microregions resulting from the yield gaps reduction for each of the four crops analyzed.

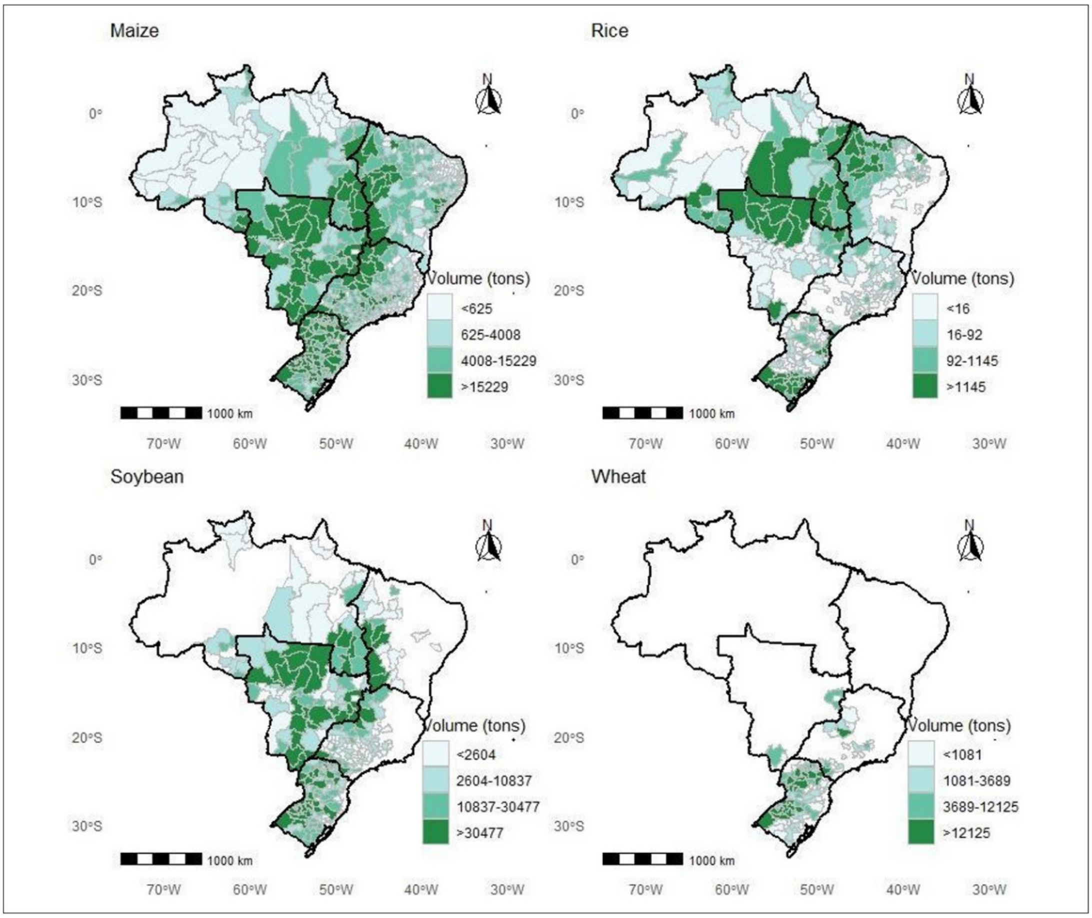

Figure 2. Microregional distribution of production gains of the main food crops in Brazil in 2017.
Source: based on data from IBGE (Instituto Brasileiro de Geografia e Estatística, 2020a).

In the case of maize, production gains resulting from the reduction of yield gaps - around 11.6 million tons - are distributed more evenly throughout the Brazilian territory than for other crops analyzed, forming a large territorial area that encompasses the entire Center-South of Brazil and extending to the Northeast region (especially in its western strip) and part of the North region (southeast of this region), as shown in Figure 2. It is important to point out that as the South region demands large volumes of maize from the Central-West region of Brazil for animal feed production, growth in production in the South of the country through yield gap reduction reduces this dependence.

In the case of rice, Figure 2 shows that the greatest potentials for production growth - totaling almost 1.0 million tons - are concentrated in the far south of the South region of Brazil, which already stands out in the cultivation of this grain, in the southeast of the North region, in the northwest strip of the Northeast region and in the northern part of the Central-West region of the country. For soybean, reducing the yield gap would imply increasing production in regions where the crop is already well established, particularly in the South and Central-West of the country, and would also advance into some microregions that make up the MATOPIBA - an acronym that designates a region that involves part of the territory of the states of Maranhão, Tocantins, Piauí, and Bahia - and which has become one of the country's most recent agricultural frontiers. Of the total of just over 5.6 million tons of soybean production increase resulting from the reduction of yield gaps in Brazilian microregions, the South and Central-West regions would be responsible for 75%. For wheat, production gains are concentrated in a few microregions in the South of Brazil, with a potential for production increase of around 805 thousand tons from the reduction of yield gaps for this crop.

4.3 Historical yield gaps for the crops analyzed

The potential production gains of the four crops evaluated in this study derive, among other things, from the variety of yields presented by the different microregions of Brazil. In this section, some additional characteristics associated with the yields of those crops in different regions of the country over time are highlighted. These regional differences result from a combination of factors (investment capacity in technology, irrigation, biophysical conditions, varieties, etc.), and have been widening among producing establishments in recent decades.

Figure 3 shows the frequency distribution of observed average yields and their changes between the years 1978 and 2017, by quantile group. For rice and maize, the growth of yields in Brazil was accelerated: 179% for maize and 210% for rice between the periods 1978/87 and 2008/2017. However, these evolutions were accompanied by a greater dispersion among yield groups, with the 25% least productive showing little growth in yield in these almost five decades. On the other hand, the 25% most productive started to present gains in yield well above average, as shown in Figure 3. New varieties, transgenics and investments in technology contributed to the emergence of producers with far above average yields, helping to further expand the participation of traditional regions in production.

It is important to highlight the specificity of the maize crop with its dual purpose: self-consumption and trade. Self-consumption refers to the portion kept on the property for its own use, whether for human or animal consumption. This occurs mainly in the case of small producers distributed throughout the Brazilian territory. The maize harvest style adopted in Brazil is mostly mechanical, except in cases such as subsistence farming or cultivation of specific varieties on small properties (mini maize, organic maize, and sweet maize), which can also be destined for local small-scale commercialization.

In the case of soybean, a visible increase in yield in all quantile groups was found. This reflects the fact that this is a crop with less diversified technological standards, being adopted by producers of different sizes in the Brazilian regions. It should be remembered that this crop increased greatly during the 2000s, a period in which planted areas grew in all Brazilian regions to serve international markets, with an even faster expansion rate in non-traditional regions such as the North and Northeast. This helps to explain why the yield gains from the gap mitigation for soybean are the smallest among the four crops evaluated (see again Table 1). Considering the annual average between the years 1978/87 and 2008/2017, the accumulated soybean yield showed an expansion of 82.3%.

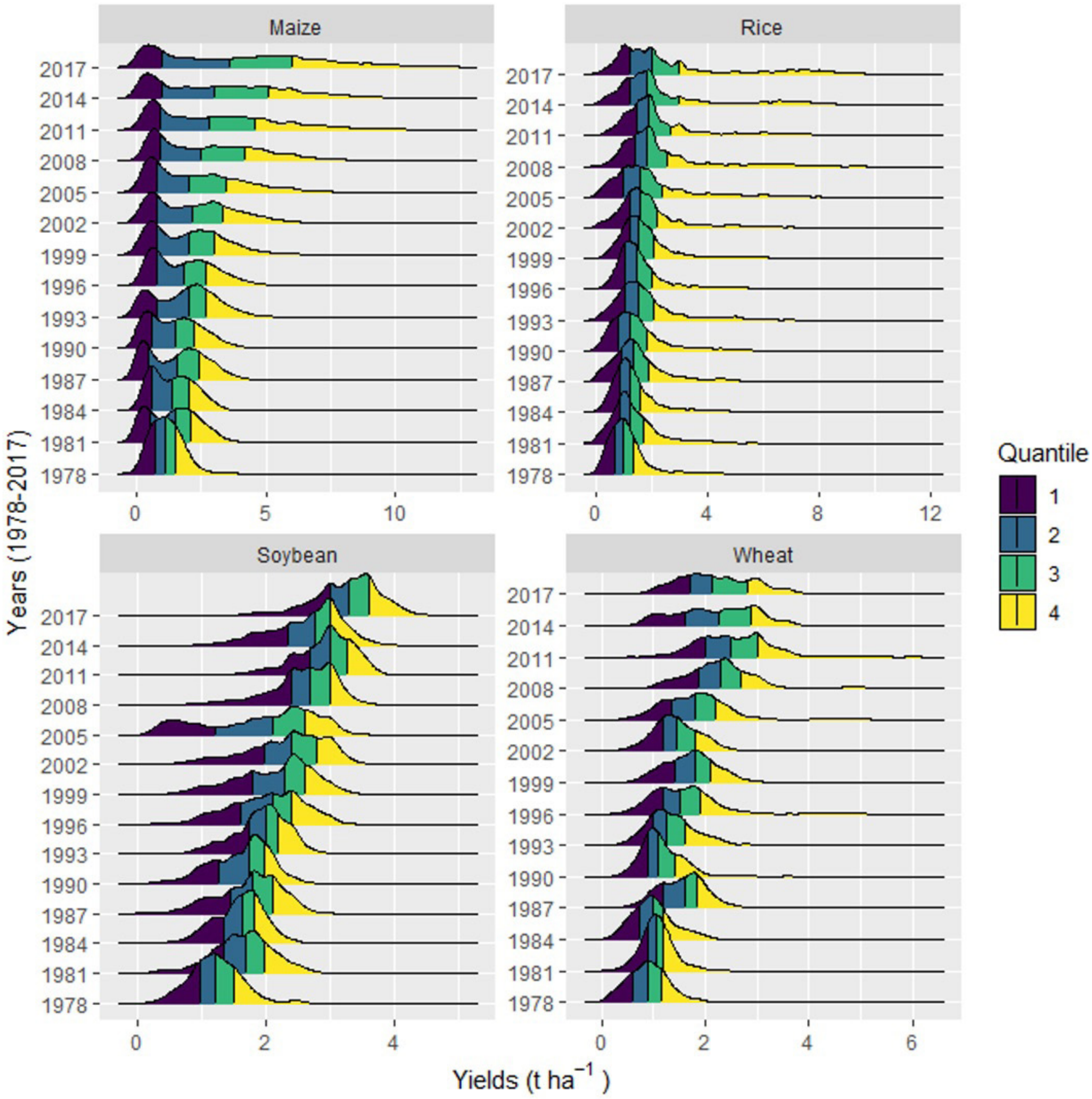

Figure 3. Yield dispersion of the main food crops in Brazil between 1978 and 2017.
Source: IBGE (Instituto Brasileiro de Geografia e Estatística, 2020b).

The wheat crop also presented an overall increase in yields in recent decades for all quantile groups in Brazil, with similarities among producing regions, but with increased dispersion among yields. The gap between the most and least productive producers has widened, although the planted areas have not shown a tendency to expansion over the last few decades. Between the periods of 1978/87 and 2008/17, wheat had a national average increase of yield of around 144.9%.

Figure 4 shows participation of the four quantile groups in the production volume in the last decades. Groups of producers with the highest yield (4th quantile group) in rice and maize – which are concentrated in the traditional South and Center-West regions – increased their share in national production volume. In the case of soybean and wheat, yield gains occur in all yield groups, thus maintaining their shares, despite fluctuations.

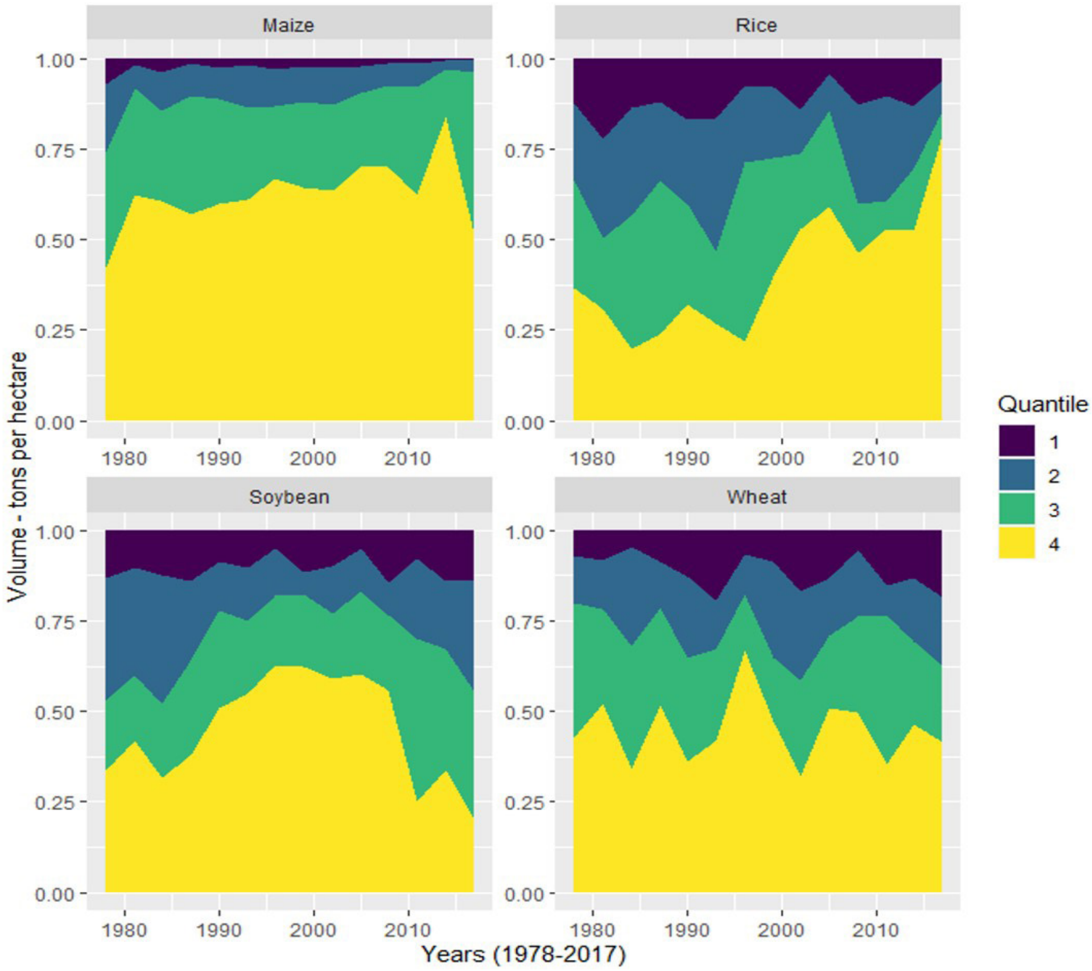

Figure 4. Production volume share of the main agricultural crops in Brazil between 1978 and 2017. **Source:** IBGE (Instituto Brasileiro de Geografia e Estatística, 2020b).

In recent decades, the growth of the Brazilian economy and its exports has encouraged the expansion and use of new technologies, allowing accelerated expansion of national food supply. According to Gasques et al. (2014), on average, 86% of the growth of the Brazilian agriculture production between 1975 and 2012 was achieved by increasing productivity, which was the result of investments in research, financing via rural credit, the opening of agriculture to the international market and adoption of new production systems.

According to Rezende (1986), since the 1970s, large producers with easier access to subsidized credit have taken the lead in the modernization process of Brazilian agriculture, benefiting from yield gains. This modernization, which accelerated in Brazil in the 1970s, spread throughout the South and Southeast of the country, through the Center-West and more recently in the Northeast and North. Helfand et al. (2015) pointed out that productivity growth and technical changes in Brazil were not generalized, diverging significantly between larger and small producers. Larger farmers have shown high levels of investment in machinery and technologies.

It must be clear that the capacity of reducing microregional yield gaps is directly conditioned by investments in technology, labor, technical assistance, and the application of existing knowledge. Even the use of irrigated systems, which contribute to mitigate climatic effects and reduce the frustrations of traditional crops, requires significant investment and technical assistance.

According to MMA (Ministério do Meio Ambiente, 2006), Brazil had about 6% of its planted area irrigated, considering the 62 main crops, which represented around 16% of the planted area. As shown in that study, there would be a potential increase of more than 26 million irrigated hectares in Brazil.

5 Conclusion

Challenges associated with food security and different types of constraints currently imposed for the expansion of food production, along with climate change, have led some researchers to point to the reduction of yield gaps as a more viable alternative for increasing the global food supply.

This study aimed to measure the yield gaps and potential production and revenue gains from the reducing yield differences among Brazilian producers for the four main food crops in Brazil and in the worldwide (rice, maize, soybean, and wheat). Based on Brazilian geographic microregions as a reference, a parameter for the potential yield of each of these crops in each microregion was estimated and the average yield attained in each municipality in the country in 2017 calculated. Using as reference the average yield obtained from the most productive group of producers in each microregion (4th quantile group), potential gains in yield with the closing of these gaps, as well as potential production and revenue gains in each microregion and at the national level, were calculated

The results revealed that the reduction of yield gaps at the microregional level in Brazil may allow the expansion of the supply of this group of agricultural products by almost 10% of the volume of 2017, equivalent to 19 million tons. Maize shows the greatest potential for growth, 13.2% in yield and production, valued at around US$ 1.7 billion (at 2017 prices). Soybean, the main crop grown in Brazil, presented the lowest potential for gains in percentage terms (5.5%); however, given the large extension of the current occupied area and the value of the product, these gains would represent US$ 1.8 billion, the highest value among the analyzed crops. The lower yield heterogeneity among soybean producers is partly explained by the requirement for a more standardized technological package. For rice, the mitigation of yield gaps would make it possible to increase the Brazilian supply by 8.8%, which represents almost 1.0 million tons and US$ 245.2 million, allowing for the supply around 19 million new consumers, which is significant given the Brazilian population. For wheat, the reduction of yield gaps shows potential for gains of 17.2% in average yield and 805 thousand tons in Brazilian production, valued at US$ 145.2 million at 2017 prices; a large part of this gains would come from the South region, which holds about 90% of the area with the cultivation of this product.

Although analyzing the factors that would allow the mitigation of yield gaps was not the objective of this study, the literature review gives indications of the main reasons for the differences in microregional yield and some necessary conditions to mitigate them. As for biophysical factors (nutrient deficiency, water stress, soil quality, losses from insects, diseases, climatic problems, and seed quality) the studies highlight that these can be managed through proper choice of location and sowing season, improvements in soil preparation, correction and soil management and by phytosanitary control. Furthermore, increasing yields would require, in some cases, scale gains in production and large volumes of investment, which is far from the reality of a significant number of producers. In this context, the role of governments by providing resources and/or the role of specialized institutions is essential.

In view of the challenges explored and those presented in the literature, future studies could address the factors related to yield gains in each Brazilian region, so that public policies more directed to each reality can be implemented. Additionally, analysis by yield groups seeking to understand the most critical factors among lower yield producers, can help guide public/private actions to ensure a growth in food supply from Brazil without the use of new areas. Another aspect highlighted by authors such as Licker et al. (2010) is related to comparisons of areas with similar soil quality and climate, but not necessarily geographically close.

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