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Abstract

Wheat production in Brazil is insufficient to meet domestic demand and falls drastically in response to adverse climate events. Multiple, agro-climate-specific regression models, quantifying regional production variability, were combined to estimate national production based on past climate, cropping area, trend-corrected yield, and national commodity prices. Projections with five CMIP6 climate change models suggest extremes of low wheat production historically occurring once every 20 years would become up to 90% frequent by the end of this century, depending on representative concentration pathway, magnified by wheat and in some cases by maize price fluctuations. Similar impacts can be expected for other crops and in other countries. This drastic increase in frequency in extreme low crop production with climate change will threaten Brazil's and many other countries progress toward food security and abolishing hunger.

Brazil's wheat production is insufficient to meet domestic demand (Conab 2020). Despite being the fourth largest producer of grains in the world, the country imports up to 6 million tons of wheat annually, particularly after years when national wheat production is extremely low (FAO 2021). Instability in crop production can threaten regional and global food security (Wheeler and von Braun 2013, Raymond *et al* 2020).

Understanding what has driven extreme production losses in the past and the frequency of those losses is a critical step in finding ways to adapt agriculture to climate change with the aim of ensuring future food availability in Brazil and elsewhere. For four major agro-climatological zones of the main wheat growing regions of Brazil (Groups I–IV, (available online at stacks.iop.org/ERL/16/104025/mmedia) supplementary figures S2 and S3), multiple regression impact models were developed to estimate wheat planting area, non-harvested area and grain yield, based on reported sub-regional wheat cropping areas, non-harvested areas, trend-corrected grain yields, monthly regional climate data, and national commodity grain prices during the period 2001–2019, as described in supplementary figures S1, S8–S11 and supplementary tables S1–S3. Wheat non-harvested area is defined as the wheat planted area destroyed by adverse weather, i.e. crop damaging weather (Trnka *et al* 2014), particularly frost and drought, and consequently not harvested. The regression results from each sub-component model (i.e. separate impact models for sub-regional wheat cropping areas, non-harvested areas and grain yield) were combined within each sub-region and then aggregated to national scale (figure 1(d)). The regression impact models, shown in supplementary table S3, reproduced regional and national planting area ($r^2 = 0.75$), harvested area ($r^2 = 0.97$), and trend-corrected yield satisfactorily ($r^2 = 0.98$), in particular the extremely poor harvest of 2006

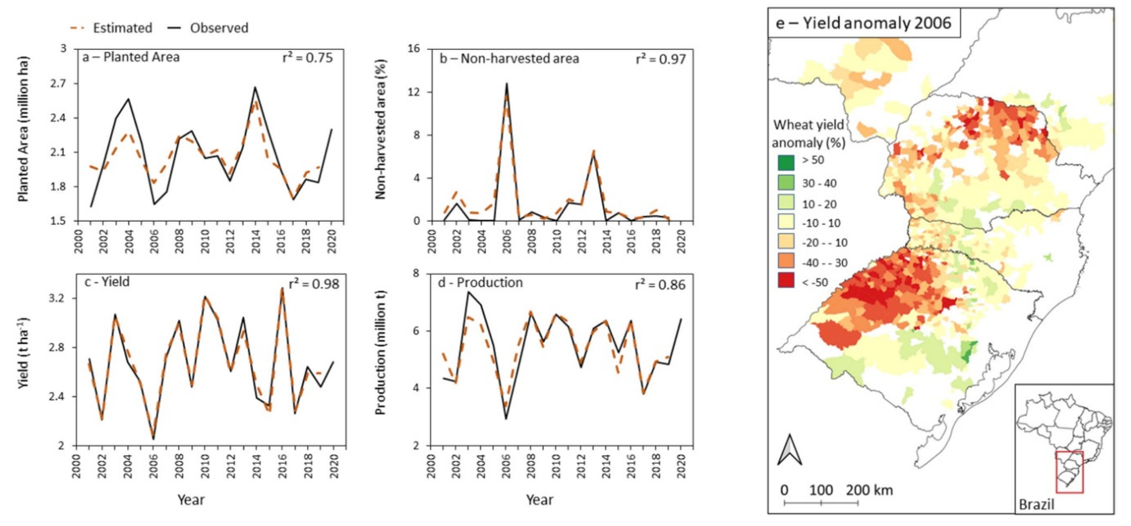

Figure 1. Observed and estimated wheat production in Brazil. Interannual variability from 2001–2020 of observed (black solid lines) and estimated (red dashed lines) (a) planted area, (b) non-harvested area, trend-corrected (c) national grain yield and (d) national grain production. (e) Trend-corrected spatial variability of the observed 2006 wheat yield anomaly. Results for individual regions are shown in supplementary figures S8–S11.

(figures 1(a)–(d), supplementary table S3). In 2006, observed low planting incentives due to low wheat prices before the cropping season and a drought during April and May, the main wheat planting period, reduced the wheat crop area by 15% (figure 1(a) and supplementary figure S5). In addition, frost damage and a drought in early spring destroyed wheat on about 12% of the cropping area (figure 1(b)). An additional drought during winter combined with low temperatures in early spring (during grain filling) reduced the remaining wheat grain yield in average by 23% (figure 1(c)), with some regional yields dropping by 50% (figure 1(e)). This compound of negative events in 2006 caused wheat production in Brazil to drop by 46%, the lowest production recorded in the last 20 years (figure 1(d)), resulting in a 60% increase of wheat price and one of the largest wheat imports in the following year (CEPEA 2020, FAO 2021).

Wheat farms in Brazil are mostly family-owned with an average size of 47 ha. The wheat planting area in Brazil is pre-determined by farmers' expectations from market signals and weather conditions during the planting period in April and May. Initially, planting decisions are driven by the wheat price before the crop season (supplementary table S2, figures S8–S11), and in the two regions, in Paraná state (Group II and III, supplementary figure S3), also by maize prices (supplementary figure S7). Subsequently, low or excessive rainfall during the planting season can further influence the decision to limit the wheat planting area (supplementary table S2, supplementary figure S20). As a result, the wheat planted area in Brazil as a whole varied by up to 0.9 million ha each year, 45% of the average 2 million ha planted yearly since 2001 (figure 1(a)). The national non-harvested area has been as large as 12% (figure 1(b)) and average national trend-corrected yields have been ranging from 3.2 t ha^{-1} down to 2.0 t ha^{-1} (figure 1(c)), which contribute to variation in national wheat production of between 3.0 and 7.5 million t year^{-1} from 2001 to 2019 (figures 1(d) and (e)). Given the ability of the multi-regression impact models in estimating planted area, non-harvested area, trend-corrected grain yield, and national production in the last two decades (figures 1(a)–(d)), we extended the analysis with long-term climate change scenarios from the recent CMIP6 ensemble for the period 1850–2100, thus considering retrospective and prospective components of climate trends. Results indicated that the wheat planted area varies from year to year, with notably more planted area when wheat prices are above average (figure 2(a)). The wheat planted area is projected to decline after 2020 because of a projected increase of up to 70% of drought events frequency during April to May, affecting wheat planting (supplementary tables S1–S2, and figures S20–S22). The projected non-harvested area fluctuates widely without a clear trend between 1% and 6% from 1850 to 2100 (figure 2(b)), with historical (1850–2000) wheat planted area losses mostly caused by frost, changing to future losses due to frequent heat, drought and excess water from high rainfall events (supplementary S21 and S22). The projected national mean yield varies between 1 to 4 t ha^{-1} with a steep declining trend after 2020 (figure 2(c)). This is mostly due to the projected future increase of up to 3 °C of maximum monthly mean temperature during wheat flowering and grain filling in July and August, on top of an already warm climate with relatively low yields, leading to heat stress and drought, further reducing grain yields (supplementary figures S20–S22) and despite the projected increase in atmospheric

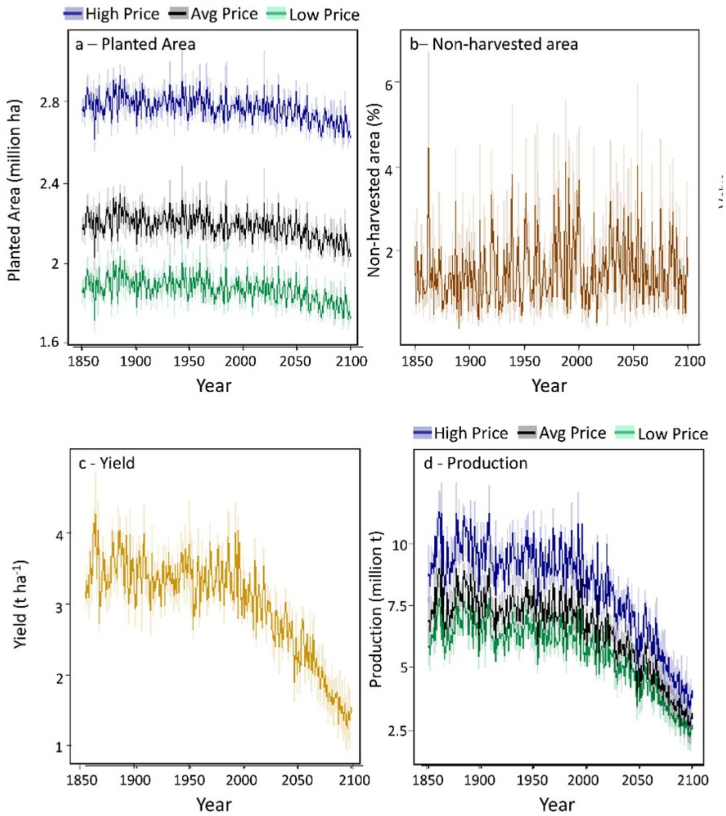

Figure 2. Wheat production in Brazil was estimated with CMIP6 global climate projections. Multi-model ensemble projections of interannual variability for (a) planted area, (b) non-harvested area, (c) grain yield (including a CO_2 growth stimulus according to Tebaldi and Lobell (2018), supplementary table S4 and figure S24) and (d) national wheat grain production, for RCP 7.0 and three fixed wheat price scenarios. Projections are a mean of five CMIP6 GCMs (lines) ± 1 s.e. (shaded areas) with regression impact models for four sub-regional wheat cropping areas aggregated to national scale. Regression impact models are separate for planting area, non-harvested areas and grain yields.

CO_2 concentration stimulating crop growth and yield (supplementary figure S24). Asseng *et al* (2017) have suggested a linear decline in absolute wheat grain yield with increasing seasonal temperatures above 20 °C, which means that the absolute yield decline is larger in warm wheat cropping regions, such as Brazil. The projected decline of wheat yields in Brazil tend to be higher than wheat yield impacts reported in other regions of the world with lower base temperatures and higher yield levels (Rosenzweig *et al* 2014, Webber *et al* 2018, Liu *et al* 2019). Estimated wheat grain yield decreases by 48 (1.5%), 75 (3.3%) and 83 (3.5%) kg ha^{-1} $decade^{-1}$ (supplementary figure S18) for Representative Concentration Pathway (RCP) 2.6, RCP 7.0, and RCP 8.5, respectively (supplementary figure S16) which would result in 20%, 50%, and 60% lower grain yields by 2100 (compared to the 1850–2020 period), assuming no adaptation is undertaken. When the projected wheat planted areas and non-harvested areas are combined in the model with projected grain yield, the national wheat production of Brazil is relatively stable under the past climate (1850–2000), but declines with climate change from 2000 onwards, regardless of commodity price signals (figure 2(d)), and again assuming there is no adaptation.

National wheat production at an average wheat price continues to decrease until 2100 by 110 000 t $decade^{-1}$ (1.5%) under RCP 2.6 and by about 180 000 t $decade^{-1}$ (2.5%) under RCP 7.0 and RCP 8.5 (figure 3). The effect of this would be an up to 60% production loss by 2100 compared to mean of the historical period 1850–2020 (supplementary figure S16), in agreement with a recent study that indicates a future decline of suitable areas for wheat in south of Brazil by up to 59% (Santi *et al* 2018). In addition, the interannual variability in national wheat production is projected to increase toward 2100 under RCP 7.0 and 8.5 (supplementary figure S19). In these scenarios, wheat production in Brazil would become more unstable and more variable before the end of the century.

Extreme low wheat production years are statistically defined as the 5th percentile of occurrence (Vogel *et al* 2021) of simulated wheat production during 1850–2020, with a low wheat price scenario, thus with a probability which occurred once every 20 years in the past. The frequency of extreme low wheat production years is projected to increase by the end of the century, regardless of RCP or wheat price (figure 4). However, extreme poor wheat harvests are projected to become even more frequent under high RCPs

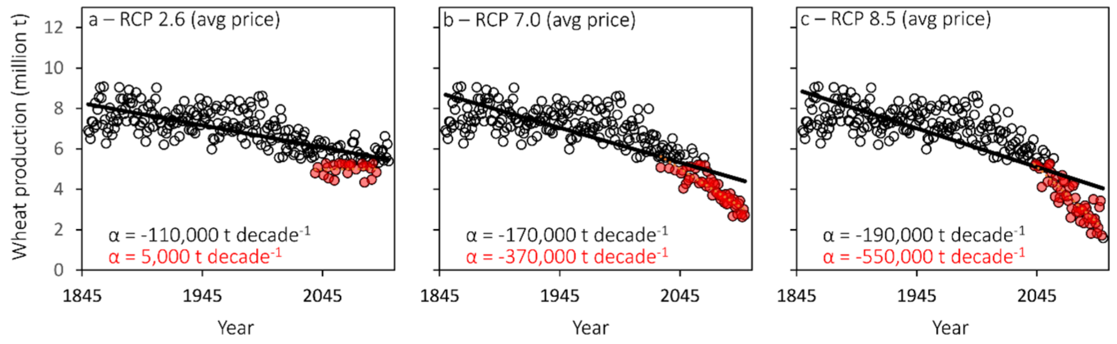

Figure 3. Projected national wheat production of Brazil. Projected wheat production for average price and for (a) RCP 2.6, (b) RCP 7.0, and (c) RCP 8.5 and an average wheat price scenario. Extreme low wheat production years are statistically defined as the 5th percentile of occurrence (Vogel *et al* 2021) of simulated wheat production during 1850–2020, with a low wheat price scenario (supplementary figure S18 for 5% occurrence during 1850–2020 for this price scenario). Data are ensemble means based on five CMIP6 GCMs. Alfa is the rate of wheat production change per decade for all wheat cropping seasons (black) and for extreme low production (red).

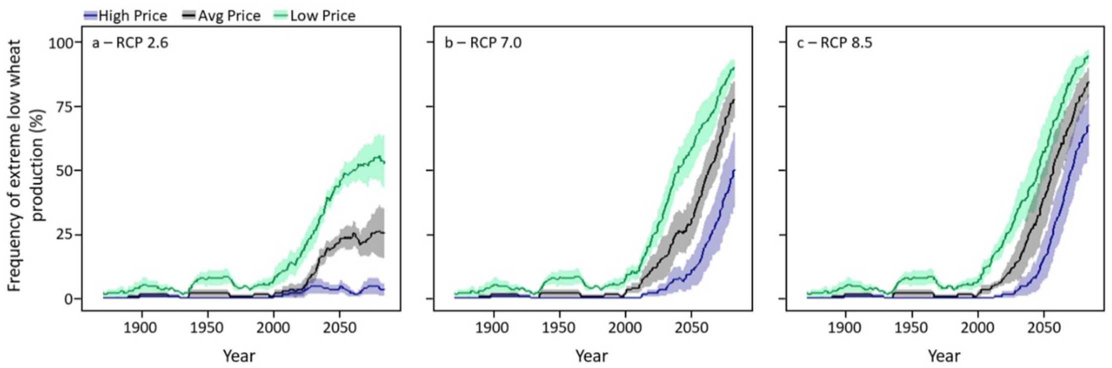

Figure 4. Projected frequency of extreme low wheat production years for Brazil. Estimated 30 years running mean frequency of extreme low wheat production for three fixed wheat prices under (a) RCP 2.6, (b) RCP 7.0 and (c) RCP 8.5 from 1850 to 2100. Lines are ensemble means based on five CMIP6 GCMs (lines) and shading shows ± 1 s.e.

and are magnified by low wheat price, and in northern wheat producing regions, also by a high maize price. For example, in the decades 2070–2100, the projections show the yearly frequency of extreme low wheat production at a national level reaches 70% when wheat prices are high, but reaches 90%, an increase of more than 15-fold, when wheat prices are low under RCP 8.5 (figures 4 and supplementary figure S17).

Extreme low production years are thus projected to become the norm in Brazil by 2100. This has parallels with future projections that extreme heatwaves in Europe (Robine *et al* 2008), as experienced in 2003, will become the norm for Europe by 2100 (Battisti and Naylor 2009). Recently reported extreme low production of wheat in France and Europe, of beans in Brazil and of maize at national to global scales (Trnka *et al* 2014, Ben-Ari *et al* 2018, Zampieri *et al* 2019, Antolin *et al* 2021) are likely to become also more frequent in the future. Indeed, the unprecedented drop in wheat production of over 30% in 2016 in France, the fifth largest wheat producer in the world, came as a total surprise to forecasters because of the unexpected impact of a combination of extreme weather events, namely warmer early winter temperatures that enabled disease spread, followed by heavy spring rainfall, waterlogging, nutrient leaching and more diseases (Ben-Ari *et al* 2018). A similar compound of extreme events, with increased drought events during the planting season, drought and heat during wheat flowering and grain filling together with high rainfalls during the wheat harvest period, causing production wheat grain losses has been observed and predicted here with the multiple regression models for Brazil, which directly account for the impact of extreme high and low temperature and variations in rainfall, while indirectly considering effects of excess water, nutrient leaching, and disease damage. The magnitude of recently experienced extreme production losses in 2006 in Brazil and the projections of extreme low production years are in stark contrast to previous climate impact studies which have largely focused on average climate change effects, essentially from increased heat and drought, with smaller yield losses and occasionally small increases computed, such as a global mean change of +1.7% for wheat (−4.5% to +3%, lower to upper quartile), of −5.8% for maize (−16%–0%, lower to upper quartile) by 2070–2100 (Rosenzweig et al 2014), and for Brazil, a national wheat production change of −5% (Liu et al 2019).

While the increased frequency of extreme lows in crop production will be a challenge for food supply, our projections further suggest that the magnitude of the shortfalls will increase, that is, the extremes will become more extreme. For example, the projections indicate that the volume of wheat harvested in Brazil in extreme low production years, when the wheat price is low, would decline from 2020 onwards by 44 000 t decade^{-1} under RCP 2.6, and by 230 000 and 300 000 t decade^{-1} under RCP 7.0 and RCP 8.5, respectively (supplementary figure S18). That means, the extreme years will become even lower in wheat production than the extreme low production years in the past.

Extreme lows in a country's wheat production, as occurred in 2006 in Brazil, impact national food security and can also have implications for global food security. For example, simultaneous wheat production failures in several exporting countries in 2008 contributed to food riots across the world (IMF 2008). And, the heatwave in Russia in 2010 destroyed one third of its national wheat production, leading to a ban on wheat export to other countries, contributing to a 50% spike in the global wheat price (FAO 2021) that is suggested to as a consequence have sparked unrest in Northern Africa (Perez 2013). A heatwave in Egypt, the largest wheat importer in the world, in the same year experienced depressed national wheat production by 13% (Asseng et al 2018) and this decline might also have added to the unrest in Egypt in the following year. These recent food crises demonstrate the sensitivity of global food security to extreme low crop production wherever it occurs. From 1964 to 2007, extreme drought and heat waves reduced global cereal production by up to 10% in some years (Lesk et al 2016), mostly affecting poor regions (FAO, IFAD, UNICEF, WFP and WHO 2018, Verschuur et al 2021). The per capita gross domestic income of Brazil, as well as that of Central Africa and India, has decreased by almost 20% due to recent global warming, accentuating global economic inequality (Diffenbaugh and Burke 2019). As extreme events from climate change increase, whether single events like heat and drought, or combinations of detrimental impacts from frost, excess water, and disease spread together with heat or drought occur, the frequency of extreme low crop production years will increase in the future. This will threaten Brazil's and many other countries progress toward food security and abolishing hunger.

Our results highlight a steep decline in wheat production in Brazil with a sharp increase with extreme low wheat production years. Alternative crops like sugar-cane, maize and pasture might be better suited to a warmer climate and an increase in these crops has been noted in recent years in south of Brazil (Conab 2020, Zilli et al 2020). The introduction of irrigation could be another adaptation to a changing rainfall pattern and a warmer climate (for crop cooling through increased transpiration), but would be costly or might not be feasible due to lack of water resources in some areas. However, in Central Brazil, recent public and private investments have started to expand wheat production with irrigation (Pereira et al 2019). To assist farmers to cope with an increase in extreme low crop production seasons, crop insurance could also become an option, but usually requires government subsidies to be affordable (Mahul and Stutley 2010).

1. Methods

Wheat planted area, non-harvested area, trend-corrected yield and production from 776 municipalities (IBGE 2020) representing 90% of Brazilian wheat production were used in a multi-model regression analysis (supplementary figure S2). Yield anomalies (Y_{anm}, supplementary figure S4) were computed as the percent difference between observed (Y_{obs}) and average (Y_{avg}) trend-corrected yield divide by Y_{avg}:

$$Y_{\text{anm}} = \frac{Y_{\text{obs}} - Y_{\text{avg}}}{Y_{\text{avg}}} \times 100. \quad (1)$$

Using yield anomalies, a hierarchical clustering analysis was performed across the municipalities and the 19 years from 2001 to 2019. As a result, four main wheat regions (Group I–IV) were defined based on their agroclimatic conditions (Scheeren et al 2008) (supplementary figure S3). Monthly maximum and minimum temperatures and accumulated rainfall recorded by National Institute of Meteorology (INMET 2021) from weather stations, from each of the four regions (supplementary table S5), thus assuming each group to represent similar climates (Scheeren et al 2008). Wheat prices, and for two regions wheat and maize prices, before the wheat cropping season were used to estimate wheat planted area. The commodity price data used were from 2005 to 2019 (CEPEA 2020). Wheat and maize prices for 2001–2004 were reconstructed with a regression relating international to domestic prices.

Statistical models were developed separately for each of the four main wheat-producing regions in Brazil. Statistical models for each region were developed for wheat planted area, non-harvested wheat area and wheat grain trend-corrected yield with municipality-based observations from 2001 to 2019, together with monthly seasonal climate records and commodity prices (before planting) (supplementary table S2). A recently suggested stepwise selection procedure for quantifying extreme crop yields (Ben-Ari et al 2018) was applied to identify the best combination of input variables using R (Version 4.0.3) (supplementary figure S1, supplementary figures S8–S11 and supplementary tables S2–S3). Similar results were obtained with the least absolute shrinkage and operator method suggested by Vogel *et al* (2021) as an alternative statistical approach (supplementary figure S23).

Monthly climate data from five CMIP6 global climate models (GCMs) for 1850–2100 were used to estimate the wheat planted area, non-harvested wheat area and wheat yield for each group, under RCP 2.6, RCP 4.5, and RCP 8.5 future scenarios (CMIP6 2020). A CO_2 growth stimulus effect on yield was included based on Tebaldi and Lobell (2018) (supplementary table S4 and supplementary figure S24). The wheat harvested area was calculated from the difference between planted and non-harvested wheat area. Wheat production was estimated by multiplying the estimated yield with harvested area. Three contrasting wheat price scenarios were applied. The high, average and low wheat prices are from a combination of the highest, average and lowest recorded wheat and wheat/maize ratio price during 2001–2019. All estimated group results were aggregated to estimate national production.

Extreme low national wheat production was estimated for each GCM separately and defined as the 5th percentile (Vogel *et al* 2021) wheat production during 1850–2020 (which as a 5% frequency is equivalent to once every 20 years), a period when all RCPs were similar and using the low national wheat price from the reference period 2001–2020.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Author contributions

RSNJ and SA conceptualized the study, all co-authors contributed to the methodology, RSNJ developed the statistical models and analyzed data, ACR assisted with climate data, TBA assisted with statistical models and statistical analysis, RF assisted with economic analysis, all co-authors contributed to data evaluation and interpretation, RSNJ wrote initial draft, all co-authors assisted with writing and reviewed the manuscript.

Conflict of interest

The authors declare no competing interests.

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