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The expansion of rainfed grain production can generate spontaneous hydrological changes that reduce climate sensitivity

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ABSTRACT

As global warming intensifies climatic extremes, the need to understand their effects on farming systems, particularly under rainfed conditions, grows. During the last three decades the Argentine Pampas, a major global grain exporter, hosted an unprecedented expansion of cultivation under unirrigated and undrained conditions. Simultaneously, the extreme flatness and lack of water infrastructure favored groundwater level raises where agriculture expanded. However, the effect of climate extremes and elevated water tables buffering droughts but increasing flooding risk on the sensitivity of regional grain production remains unknown. Based on agronomic, weather, water table, and remote sensing data, we analyzed the production response to dry, wet, and flooded periods over the last 35 years, and to the ongoing water table raises during the last 15 years, focusing on sown and effective harvested area (harvested/sown area) and yield. Soybean and maize production increased 5.9 and 3.3-fold, respectively, as a result of area and yield growths. On average, droughts decreased production (−25 % for soybean and −14 % for maize) and wet periods increased it (+14 % for soybean and +17 % for maize) through their effects on yields and effective harvested area. Floods reduced production (−8 % for soybean and −10 % for maize) by decreasing sown and effective harvested area, leaving yields unaffected. As water tables rose, a positive yield effect during drought was detected, with counties with shallow water tables (< 3 m depth) halving yield cuts during dry years. Lacking water infrastructure, this South American grain belt is currently matching the annual production variability levels observed under intense irrigation and drainage in North America. The unexpected water table level raises of the Pampas had an overall positive effect on grain production, with flood disruptions being more than compensated by drought buffering. This balance may change in the future, calling for a deeper understanding of these complex relationships between climate, hydrology and agriculture.

1. Introduction

In a context of climate change that challenges agricultural systems, the growing global demand for food pushes agricultural regions of the world to increase their production (FAO, 2015; Pielke, 2005; Thornton et al., 2014). While some global breadbaskets tackled this challenge through intensifying the cropping systems, for instance by increasing the proportion of irrigated area (West et al., 2014), others opted for an expansion of the rainfed cultivated area (Potapov et al., 2022; Song et al., 2021). Although global food production shows a growing trend as a result of both processes (Pellegrini and Fernández, 2018; West et al., 2014), it is critical to understand the sensitivity of crop production components (e.g., cultivated and harvested area, grain yield) to extreme weather events particularly considering they are expected to continue to increase their intensity and frequency (Greve et al., 2014).

Weather variability, along with other environmental, market, and political factors, influences crop production through diverse mechanisms (Li et al., 2019; Santini et al., 2022). Drought events are known as

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the major cause of crop yield reductions in rainfed agricultural systems (Lobell et al., 2020; Rötter et al., 2018; Zipper et al., 2016). The production deficit due to droughts reached 19.9 % in the most technically developed agricultural systems of North America, Europe, and Australia, whereas in less technified systems of Asia and Africa this deficit varied between 9.2 % and 12.1 % (Lesk et al., 2016). Recent studies have shown that the combination of drought with high temperatures amplifies grain yield reductions (Schauberger et al., 2017), although their impact is cushioned by a growing reliance on irrigation across Asia and North America (Li et al., 2019; West et al., 2014). Although genetic improvements and better management techniques can help to better deal with droughts (Hall and Richards, 2013; Pellegrini and Fernández, 2018), the prediction of an increase in its intensity and frequency for some global breadbaskets, such as the Pampas in central Argentina (Barros et al., 2015; Messina et al., 1999), is particularly relevant since a stronger impact on the agricultural production would be expected given the lack of irrigation.

The impacts of water excess on crop production have received considerably less attention than droughts. Extreme precipitation events, flooding, and waterlogging are responsible for production loss due to multiple factors such as poor oxygen (and soil water) uptake by crop roots, nutrient deficiency due to leaching, physical plant damage, and interference with agronomy practices (e.g., sowing or harvest) (Rötter et al., 2018; Trnka et al., 2014). A global analysis did not identify an effect of floods on crop production (Lesk et al., 2016), likely reflecting the fact that the negative local impacts are offset or even surpassed by the overall positive effects brought by higher water availability at the regional level (Thornton et al., 2014). Still, under the more humid conditions of Europe, water excess has a stronger negative impact than droughts on wheat production (Zampieri et al., 2017), and in North America maize yield loss due to excessive rainfall have been comparable to those caused by extreme drought (Li et al., 2019). In the Southern Hemisphere, whilst the Australian farmlands showed that sown area reductions resulting from waterlogging ranged between 1 and 3.8 million hectares (Setter and Waters, 2003), the sensitivity of South American farm belts to water excess remains poorly understood (Fraisse et al., 2008; Jozami et al., 2018; Nóia Júnior et al., 2019).

The Argentine farm belt, and particularly the Pampas region, is a main component in global grain exports (Aguiar et al., 2020). However, the lack of regional studies focused on grain production sensitivity to both extreme droughts and floods hinder our ability to understand and assess any climate change impact on world supply-demand grain scenarios. While most grain-cultivating regions of the world showed steady production increases, aided in part by increasing irrigation, in the Argentine Pampas grain production has grown at an unprecedented pace maintaining its unirrigated and undrained condition, but accompanied by water table raises attributed in part to its own expansion towards drier areas (Piquer-Rodríguez et al., 2018; Viglizzo et al., 2011). Likewise, this lack of drainage infrastructure in an extremely flat landscape hinder the removal of water excesses (Aragón et al., 2011; Kuppel et al., 2015), and may determine a particularly high sensitivity to surplus rainfall. Therefore, the Pampas region provides a unique setting to explore the sensitivity of farming to climate fluctuations, including droughts, floods, and water table level rises, under an almost complete lack of irrigation and drainage interventions, in contrast to other grain belts that experience deepening of water tables due to increased irrigation (Famiglietti, 2014).

In the Pampas, the replacement of large areas of perennial pastures by annual crops during the last decades lead to more positive water balances (i.e., evapotranspiration reduction) and increased groundwater recharge (Nosetto et al., 2012, 2015). Simultaneously, a regional increase in precipitation has also been registered particularly during the 1990s and 2000s (Vera et al., 2006), which together with the recent changes in land use and land cover have disrupted the water balance leading to changes in historical floods and droughts cycles, and shallower water tables (Alsina et al., 2020; Jobbágy et al., 2008; Viglizzo et al., 2009). Partially related to the El Niño Southern Oscillation (ENSO), these cycles dictate extreme weather events with observed but poorly systematized consequences on grain production (Messina et al., 1999; Podestá et al., 1999). Whereas drought episodes mainly affect crop yields regionally, rainwater excess triggers waterlogging and flooding processes capable of generating local crop damage and interfering with sowing and harvesting (Viglizzo and Frank, 2006); however, shallow water tables can also increase crop yields at paddock scale, particularly in dry periods (Nosetto et al., 2009; Vitantonio-Mazzini et al., 2021). Therefore, knowing the effect of extreme weather events in a context of hydrological change will help to understand large scale agricultural responses under a unique combination of modern farming technologies with minimum inputs (e.g., fertilizers) (Jobbágy et al., 2021), almost nil irrigation and a lack of drainage of farmlands, not seen in other breadbaskets of the world.

In this study, we analyzed the crop production trend in the Pampas with special focus on the responses of production components to extreme climatic conditions (dry, wet, and flooded years), during the last 35 years, a period in which this region experienced its most rapid farming expansion in history accompanied by steady water table level raises (Alsina et al., 2020; Song et al., 2021). Based on county level agricultural surveys of cropland production, climate and groundwater level records, and satellite information, over counties where agriculture expanded earlier, hereafter Pampas core, and counties where agriculture expanded later, hereafter Pampas periphery, we (i) analyzed the spatio-temporal trends in production and its components (i.e., sown area, effective harvested area, and yields) for the two most important crops of the region (soybean and maize) between 1985 and 2019, and quantified the response of these variables to extreme dry and wet events (i.e., annual growing cycles with high and low annual precipitation anomalies) and flooded periods (i.e., long-lasting episodes of high water-covered area); and (ii) assessed the role of current hydrological changes (i.e., shallower water tables) buffering production fluctuations over the second half of the study period.

Two opposing hypotheses guide our study. On the one hand, we hypothesize that (i) as agriculture expands towards marginal zones in the Pampas periphery, the sensitivity of agricultural production to climatic variations increases in comparison with the Pampas core. Given the rainfed condition of crop production in the whole Pampas region, its grain yield is highly dependent on the rains occurring during the crop cycle, which usually show higher relative variability towards drier marginal zones (Maddonni, 2012; Magliano et al., 2015). While the mean yield values may still increase as crop productivity improvements compensate for the expansion into more marginal lands, we expect that the yield variability will increase through time because of the negative effects of dry years and the positive effects of wet years get amplified. In the opposite way, we also hypothesize that (ii) the widespread water table rise that has occurred in recent years in the region decreases the sensitivity of crops to climatic conditions. In many zones, historically deep water tables have risen to levels close to the ground surface, favoring the supply of groundwater to crops particularly during dry periods (Alsina et al., 2020; Nosetto et al., 2009). However, it is also likely that shallow water table increases root anoxia problems during humid periods, thus reducing their positive effects on crops (Florio et al., 2014; Kahlown et al., 2005). As a consequence, we expect that the temporal variability of maize and soybean production tend to decrease in the last half of the study period, particularly in those counties with shallow water tables.

2. Materials and methods

2.1. Study design and crop production data sources

The study area extended over 269,557 km^2 in the Argentine Pampas (Fig. 1a), and encompassed 59 % and 48 % of the total area dedicated to grain crops in the country in 1985/86 and 2018/19 growing seasons,

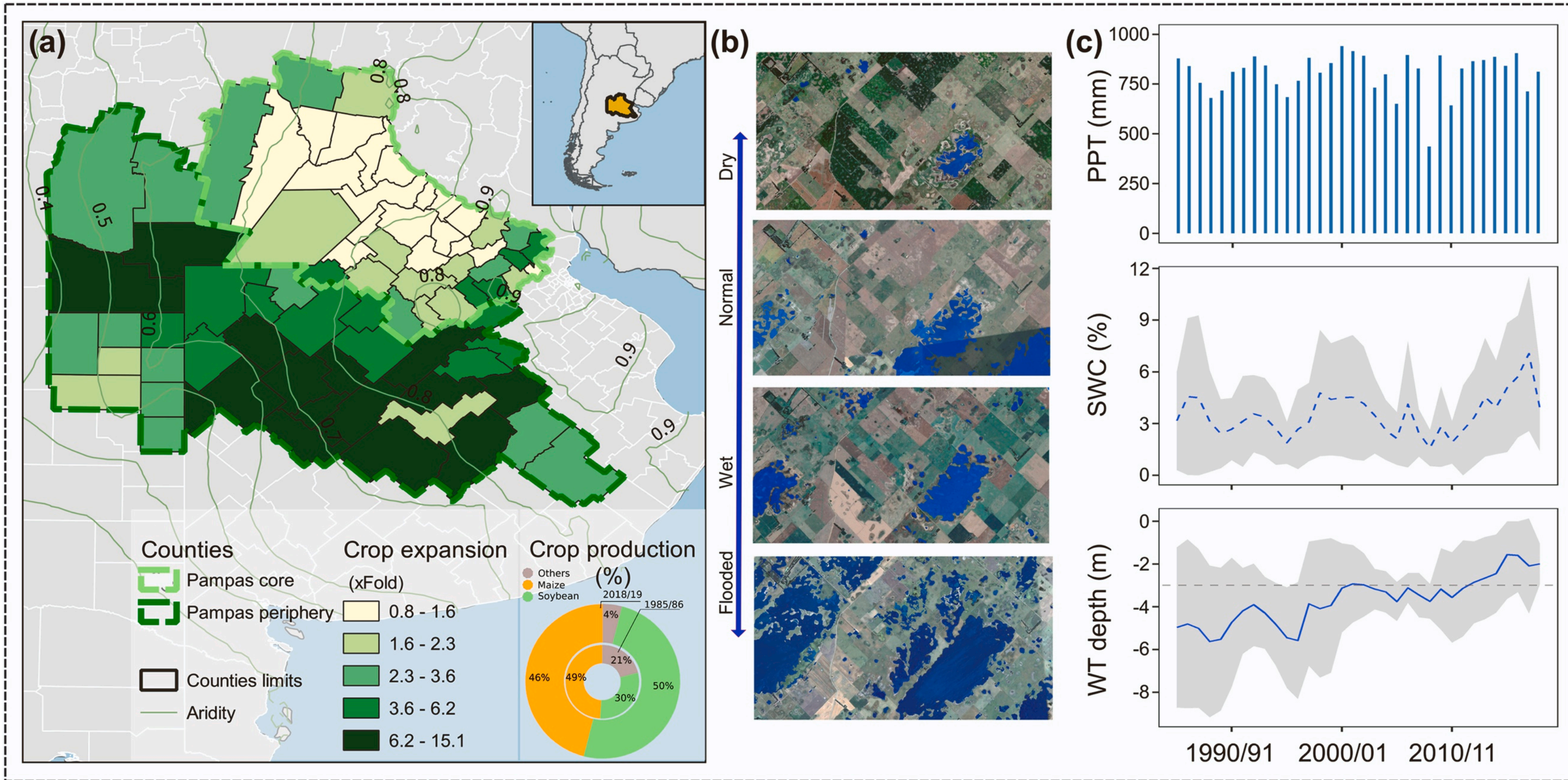

Fig. 1. Map of the study area in the Argentine Pampas (a), showing the crop expansion (xFold) in the Pampas core and periphery, the aridity index isolines (ratio between precipitation and potential evapotranspiration) as a proxy of water availability (green lines), and the proportion of grain production for dominant summer crops in 1985/86 and 2018/19 seasons. Differences in size of pie charts refer to the expansion of grain production between the first and last studied crop season (absolute value of 5.6 and 9.1 in 1985/86 and 32.7 and 30.3 Mt in 2018/19 for soybean and maize, respectively). (b) Satellite images of farmlands under different climatic conditions. (c) Mean annual precipitation (PPT), surface water cover (SWC), and water table (WT) depth from 1985/86–2018/19 seasons. In panel c, the horizontal gray dashed line indicates when the water tables were or were not accessible to soybean and maize, assuming a threshold of 3 m depth. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

respectively. This area produced 67 % and 55 % of total grain production in the country in 1985/86 and 2018/19 seasons, respectively (Argentine Ministry of Agriculture, Livestock and Fisheries; http://datosestimaciones.magyp.gob.ar/). The whole study area involves 76 counties (i.e., the smallest administrative unit in Argentina), grouped into the Pampas core (38 counties; 93,690 km^2) and Pampas periphery (38 counties; 175,867 km^2; Fig. 1a; Table A.1). The region was originally covered by native grassland (Soriano et al., 1992) but, as we stated previously, in the Pampas core agriculture expanded earlier (decade of the 1960 s) and at the beginning of the study period a large area was already destined for agriculture (SE of Córdoba, S and center of Santa Fe, and N of Buenos Aires province). By contrast, in the Pampas periphery agriculture expanded more recently replacing implanted pastures, native grasslands and wooded patches (S of Córdoba, N of La Pampa, and W and center of Buenos Aires province; Viglizzo et al., 2011). The landscape is flat in the whole region, containing soils that are mostly Mollisols. Predominant soils of the Pampas core are deep sandy loams (Typic Hapludoll and Entic Hapludoll) and shallower clay loams (Typic Argiudoll and Aquic Argiudoll), and soils of the Pampas periphery are deep Entic Haplustolls that have a sandy texture and do not present any significant restriction to crop growth. Sand content usually exceeds 70 % and the soil organic matter in the top horizon is < 1.5 % (INTA-SAGyP, 1990). The climate is temperate with mean annual temperature ranging from 18° to 14°C along a N-S gradient (Diaz-Zorita et al., 1998). Rainfall decreases from NE of the Pampas core to SW of the Pampas periphery (Fig. 1a) and it is concentrated during the summer and the beginning of autumn with a decline during winter particularly towards the NW (Magliano et al., 2015).

To analyze the spatial and temporal patterns of soybean and maize production and its components we used data from the Argentine Ministry of Agriculture, Livestock, and Fisheries (MAGyP, Ministerio de Agrícultura, Ganadería y Pesca; http://datosestimaciones.magyp.gob.ar/). From 1985/86–2018/19 seasons, we analyzed the county-level data for these two dominant crops, which reached 79 % and 96 % of summer grain production in the 1985/86 and 2018/19 seasons, respectively (Fig. 1a). Winter crops (i.e., wheat) were excluded from the analysis because they represent a minority proportion, particularly during the second half of the analyzed period (they add 11 % of total grain production per season). The agronomic data included grain production, sown area, effective harvested area (i.e., absolute values of harvested area divided by absolute values of sown area; thereafter called 'harvested area fraction'), and grain yield of soybean and maize. Sown area is used in two different ways; first in absolute terms (hectares) as a component of total production [production (t) = mean yield (t ha^{-1}) x sown area (ha) x harvested area faction (dimensionless)], but also in relative terms as a descriptor of agricultural extent across different territories (i.e., Argentine Pampas, Pampas core, Pampas periphery, and individual counties). In this last case, sown area is expressed as the percentage of the total area of the given territory under analysis (%). The agricultural data of MAGyP are annually collected from multiple sources, including field sampling, estimations made by qualified advisors (e.g., data obtained from farmers, agronomists, grain cooperatives, and traders), and remote sensing data. The MAGyP database does not divide long-term data in early-sown and late-sown crops, therefore the analysis of sown area grouped these two different crop management strategies.

2.2. Precipitation data

The long-term precipitation data (1985–2019) was obtained from meteorological stations of the National Institute of Agricultural Technology (INTA; https://www.argentina.gob.ar/inta), National Meteorological Service (SMN, https://www.smn.gob.ar/), Ministry of Agriculture and Livestock of Córdoba province (https://magya.omixom.com/), Secretariat of Water Resources of La Pampa province, and the Institute for Large Plains Hydrology network (IHLLA; https://www.ihreda.com.ar/). We used 27, 33, 16, 29 meteorological stations located in Buenos Aires, Córdoba, Santa Fe and La Pampa provinces, respectively. Precipitation data were simply averaged when there were two or more stations available for the same county. In the cases where field data were not available, we used the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS; https://www.chc.ucsb.edu/data/chirps). CHIRPS platform estimates precipitation based on rain gauges and remote sensing observations at monthly temporal and 0.05° spatial resolutions. Accumulated monthly precipitation values per county were used to calculate annual values at county level. In our study, annual precipitation data spanned from September 1st of a given year to June 30th of the next year, corresponding to the early sowing and late harvest period, respectively (INTA; https://www.argentina.gob.ar/inta).

2.3. Water surface cover data

We estimated the surface water cover (SWC, %) using the JRC Monthly Water History, v1.2 product, developed by the Joint Research Center (Pekel et al., 2016) and visualized in Google Earth Engine. The JRC product contains a dataset with more than 4 million scenes from Landsat 5, 7, and 8 acquired between 16 March 1984 and 31 December 2019, and uses an expert system to detect and classify each individual pixel (30 m resolution) into water / non-water with an accuracy of 90 %. The product outputs involve the entire history of water detection on a month-by-month basis. We calculated the monthly and annual SWC percentage per each county taking into account its size published by the National Geographic Institute of Argentina (IGN; https://www.ign.gob.ar).

2.4. Determination of extreme weather events

We used precipitation anomalies during the crop growing seasons to determine extreme dry and wet events and normal years, and the anomaly of the surface water cover to define flood episodes over the 35 years. The anomaly defines the degree to which precipitation (and surface water cover) deviates from its mean state to detect dry and wet years (and flood episodes) based on the approach presented by Li et al. (2019). We first calculated the standardized anomaly of precipitation (SA_{ppt}; also known as standard score) for each county and crop season, following Eq. (1):

$$SA_{ppt} = Y_{ij} - Y_{mean\ j} / \sigma_j \tag{1}$$

where Y_{ij} is the precipitation of a given year i and county j, $Y_{mean\ j}$ is the long-term precipitation average, and σ_j is the standard deviation of the study period per county, respectively. We later obtained a mean SA_{ppt} value for the whole study area per each year. The precipitation standardized anomalies ranged from − 1.99–1.56 during the 1985–2019 period, and these data were used to define dry (low precipitation) and wet (high precipitation) extreme events as anomalies below the 20th percentile and above the 80th percentile, respectively. Normal years were defined as those seasons with precipitation anomalies closer to zero, including the first three positive and negative values (see details in Table A.2). The extreme wet seasons that coincided with flooding episodes (i.e., 2000/01, 2001/02, 2002/03 seasons) were grouped into flood episodes (Fig. 1b). The dataset combined 7 dry events, 4 wet events, and 6 normal years from 76 counties over the 1985–2019 period. We also corroborated the year of each extreme event with technical reports published by the National Institute of Agricultural Technology (INTA; https://www.argentina.gob.ar/inta).

We calculated the standardized anomaly of surface water content (SA_{swc}; based on Eq. 1) per county at a given year. We used anomalies above the 80th percentile to define flood episodes. The study area registered three clear flood episodes (Fig. 1c) during the 1985–2019 period, which were also supported by previous bibliography (Aragón et al., 2011; Houspanossian et al., 2018; Kuppel at al, 2015). One flood episode lasted two seasons from 1986 to 1988, another lasted three growing seasons from 2000 to 2003, and the last one lasted two seasons from 2015 to 2017. Each flood event was not spatially homogeneous across all counties. In particular, flood peaks in the last episode (2015/16–2016/17) occurred in 2015/16 for the Pampas core and in 2016/17 for the Pampas periphery. The maximum area covered by surface water bodies in the flooding episodes of 1986/87–1987/88, 2000/01–2002/03, and 2015/16–2016/17 approached for 4.6 %, 4.9 % and 7.7 % of the whole study area, respectively, being 3.6 % during the rest of the time (Fig. 1c).

2.5. Water table data

We compiled time series data of monthly water table depth from 2005 and 2019, the period with the most abundant and complete records distributed around the whole region. Field data were obtained from 323 wells managed by the National Institute of Agricultural Technology (INTA; https://www.argentina.gob.ar/inta), National Meteorological Service (SMN, https://www.smn.gob.ar/), Secretary of Water Resources of La Pampa province, the Institute for Large Plains Hydrology network (IHLLA; https://www.ihreda.com.ar/), and particularly farmers and agronomists. In the cases where water table records were not available in a county, we estimated the water table depth based on a regression model developed by Kuppel at al. (2015) for the Pampas. These authors fitted a model between monthly averages of groundwater depth and terrestrial water storage ($R^2 = 0.78$), which is the total vertically integrated water stored above and below the Earth's surface. We obtained monthly data of terrestrial water storage from the Gravity Recovery And Climate Experiment (GRACE) (Landerer and Swenson, 2012).

2.6. Statistical analysis

To accomplish our first objective, we analyzed the variation of soybean and maize production, sown area, harvested area fraction, and yield over the 1985–2019 period. In the cases of production, sown area, harvested area fraction, these analyses used both combined crop data (i.e., sum of soybean and maize data) and segregated data for each crop. To determine the mathematical model that best describe observed data we used linear regression models and segmented regression models (also known as broken-line regression models), using functions of the R package 'mass' and 'segmented'. Segmented package is aimed to estimate linear and generalized linear and nonlinear models having one or more segmented relationships in the linear predictor (Muggeo, 2008). The algorithm used by segmented is an iterative procedure that needs starting values only for the breakpoint parameters and therefore it is quite efficient even with several breakpoints to estimate. Complementary, we fitted the best regression models that explained the fluctuations of coefficient of variance (CV) of soybean and maize yield among counties over 35 years in the Pampas core and periphery, and also, the fluctuations of CV of soybean and maize yield and the mean water table levels over the 2005–2019 period in each subregion. In all cases we used the Akaike's information criterion (Akaike, 1974) to obtain the best fitted equation.

In order to quantify the impact of extreme events (i.e., dry, wet, and flooded years) on grain production and its components, we used a subset of the time series of agricultural data taking into account a 5-year window centered on the year when the focal extreme event or normal year occurred (i.e., 0 year), with two non-extreme years of data preceding (−2 and −1 years) and following (+1 and +2 years) each event, following Lesk et al. (2016). When a pre- or post-focal year involved another extreme event, they were replaced by the next consecutive year backward or forward. For the 1986–1988, 2000–2003 and 2015–2017 flood episodes (i.e., multi-year flood) we averaged each agricultural variable to produce a single extreme year datum (i.e., mean data was assigned to year 0). For the last flood episode, we assigned '0 year' to the agricultural data in 2015/16 at the Pampas core and in 2016/17 at the Pampas periphery due to shifts in the flood peak timing (details in Section 2.4). After we defined the 5-year window composition, absolute values of grain production, sown area, harvested area fraction and yield were normalized to the average of the two years preceding and following the event (X_{mean}) to remove the absolute magnitude of the subset data from the event signal, following Eq. (2):

$$\text{Normalized variable} = X_{ij} / X_{mean\ j} \tag{2}$$

where X_{ij} is the absolute value per each year i (i.e., 5-year window: −2; −1; 0; +1; +2 years) and per county j, and $X_{mean\ j}$ is the average of absolute values of pre- and post- event years (i.e., −2; −1; +1; +2 years) per county, excluding the focal year (i.e., 0 year). This methodology had the advantage of minimizing other potential effects of changes in management practices and genetic improvements on crop production over the 5-year window. We used general linear mixed models (GLMMs; Zuur et al., 2009) to analyze differences between the focal extreme event and focal normal year for each normalized variable in the whole Pampas region and subregions (core and periphery). We considered focal years (i.e., extreme events and normal years) as fixed factor and counties as random factor.

To accomplish our second objective, we first used the depth value of water tables at the beginning of each growing season (i.e., September) per each county to determine when water tables were, or were not, accessible to soybean and maize in each season (from 2005/06–2018/19), assuming a threshold of 3 m depth (Nosetto et al., 2009). Therefore, we denominated 'county with water table' when its depth fluctuated between 0 and 3 m and 'counties without water table' when its depth was > 3 m. Secondly, we calculated the average yield change of soybean and maize to evaluate the yield response to precipitation anomalies spanning from extreme dry to extreme wet conditions (details in Section 2.4) in counties with and without water table over the 2005–2019 period. The yield change was calculated as the yield anomaly divided by the expected yield from their long-term trend based on Eq. (3):

$$Yc\ (\%) = (Yield_{ij} - Yield_{trend}) / Yield_{trend} \times 100\ \% \tag{3}$$

where $Yield_{ij}$ is the observed yield of a given crop season i and county j, and $Yield_{trend}$ is the estimated yield from the linear model previously fitted. We analyzed yield change differences (soybean and maize) between precipitation anomalies, water table accessibility, and its interaction in the whole Pampas region and subregions (core and periphery), using GLMMs. For this analysis we grouped precipitation anomalies into nine classes involving intervals of 0.5, and two classes involving negative (dry conditions) and positive anomalies values (wet conditions). In the cases where we found significant statistical differences in each model, we did a Tukey's test. All statistics analysis was done using R v.3.4.0 (Core Team, R.C, 2017) and its packages (mass, segmented, multcomp, ggplot2, gridExtra). A P-value of 0.05 was used as a statistical significance threshold.

3. Results

The Argentine Pampas showed a consistent grain production increase of the two dominant crops (soybean and maize) during the past three decades (1985–2019) ($P < 0.001$), resulting from higher sown area ($P < 0.001$) and yield ($P < 0.001$) (Fig. 2), but at different rates between subregions (Fig. A.1). In the whole region, while soybean production increased 5.9-fold with a peak of 35.6 Mt in 2014/15 and a maximum increment rate of 1.3 Mt yr^{-1}, maize production increased 3.3-fold, reaching a peak of 30.3 Mt yr^{-1} in 2018/19 boosted by an increment rate of 2 Mt yr^{-1} over the last decade (Fig. 2b). Increasing trends in soybean and maize production became more pronounced in the Pampas periphery than in the core since the second half of the study period (e.g., soybean production increased 29-fold in the periphery), mainly explained by breakpoints in the sown area rather than in yield (Fig. A.1). The sum of sown area of soybean and maize showed a

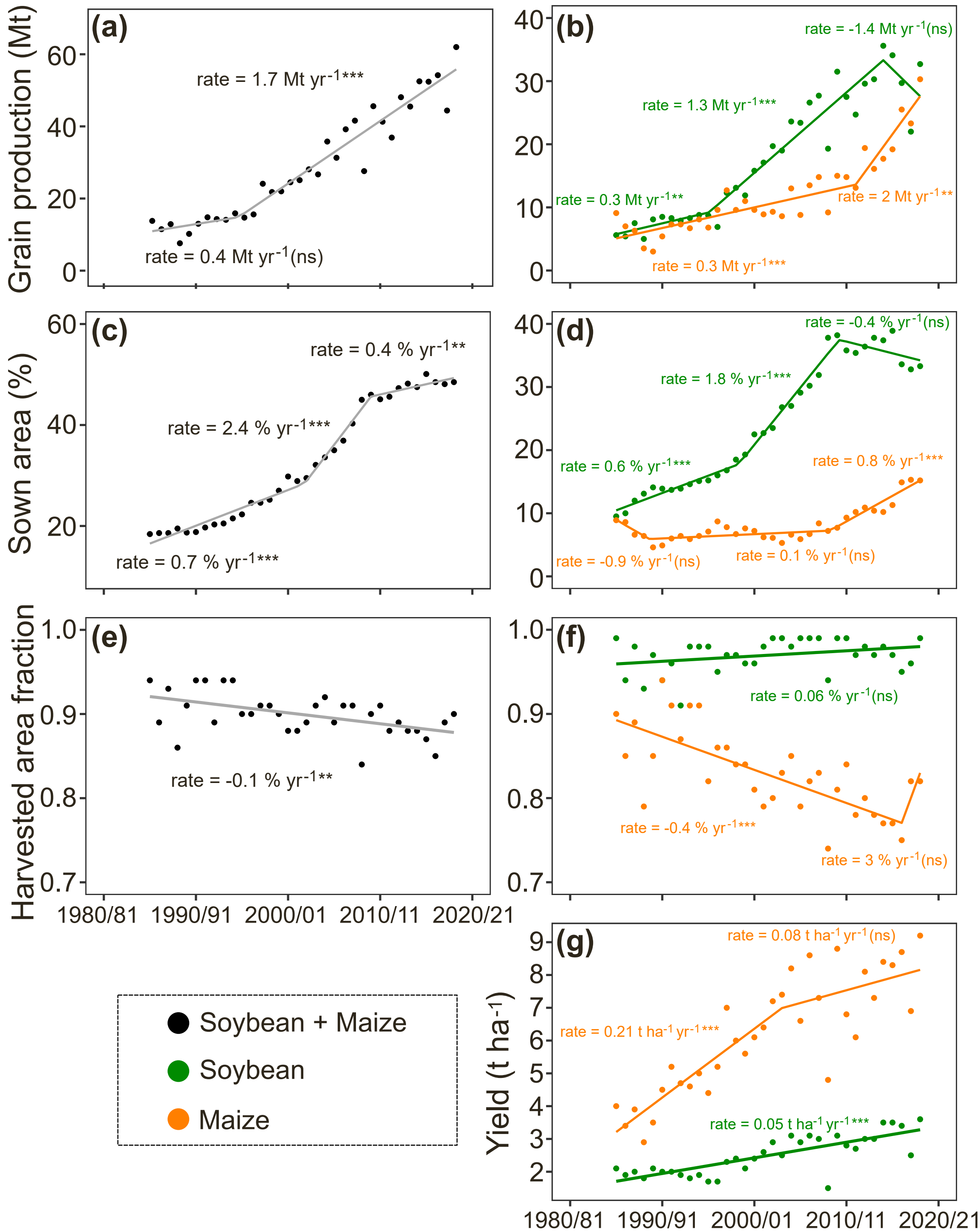

Fig. 2. Spatio-temporal changes in (a) grain production of the sum of soybean and maize, (b) grain production of soybean and maize, (c) sown area of the sum of soybean and maize, (d) sown area of soybean and maize, (e) harvested area fraction of the sum of soybean and maize, (f) harvested area fraction of soybean and maize, and (g) yield of soybean and maize from 1985/86–2018/19 seasons in the Argentine Pampas. The sown area characterizes the extent of soybean and maize crops in the Argentine Pampas. Sown area is calculated as the proportion of the area (%), while harvested area fraction is calculated as the absolute values of harvested area (ha) divided by absolute values of sown area (ha). Solid lines are the best-fit curves of linear regression models and segmented regression models (also known as broken-line regression models). The rate of changes of the fitted curves are shown inside the panels, while the values of the Akaike's information criterion (AIC) and breakpoints are shown in Table A3. The asterisks indicate the significance of the slopes (** $P < 0.01$; *** $P < 0.001$), while letters ns indicate non-significant results. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

sustained increase at a maximum rate of 2.4 % yr^{-1} up to a breakpoint in the 2009/10 season when increments ceased, adding up to 8.6 million hectares of new agricultural lands (Fig. 2c; Table A.3). Soybean was the main crop that boosted the growth of sown area, particularly from 1998/99–2008/09 period (rate of 1.8 % yr^{-1}) when it began to decline, coinciding with a rebound in the area planted with maize (rate of 0.8 % yr^{-1}) (Fig. 2d). On average, harvested area fraction indicated that more than 90 % of the sown area of the two main crops (soybean + maize) was harvested in the Argentine Pampas, although trends showed a constant decrease in this variable, but at an extremely low rate ($P < 0.01$; Fig. 2e). Particularly, this trend was caused by a decrease in the fraction of harvested area in maize ($P < 0.001$) rather than in soybean ($P = 0.8$), which maintained its fraction constant. (Fig. 2f).

The whole region trends in soybean yield showed a steady increase over the study period at a rate of 50 kg ha^{-1} yr^{-1}, reaching yield values of 3.6 t ha^{-1} in the last years ($P < 0.001$; Fig. 2 g). Meanwhile, maize yield increased at a rate of 210 kg ha^{-1} yr^{-1} for the first fifteen years ($P < 0.001$), and then slowed to a slightly lower rate of 80 kg ha^{-1} yr^{-1} ($P = 0.3$) with maximum yield values of 8.8 t ha^{-1} (Fig. 2 g; Table A.3), mainly explained by a breakpoint in the Pampas periphery (Fig. A1g). For both crops, the trends in the spatial coefficient of variation of yields over 35 years showed up and down oscillations in the Pampas core, but the best-fitted curves remained constant, showing a marginally significant decreasing slope for maize (Fig. 3a,c). Nonetheless, the yield variability increased in soybean across the Pampas periphery up to a breakpoint in the 2008/09 season when increments ceased and started to decrease ($P < 0.05$; Fig. 3a), while the variability of yield maize remained constant up to 2012/13 when it decreased sharply ($P < 0.001$; Fig. 3c). We also found a decrease in the soybean and maize yield variability as the mean water table rose over the 2005–2019 period (Fig. 3b,d), particularly in the Pampas periphery ($P < 0.001$).

In comparison with normal years, both dry periods and flood episodes negatively impacted on soybean and maize production and its components, while wet periods caused positive responses in the Pampas region (Fig. 4). However, these patterns were more pronounced in the Pampas periphery than in the core (Fig. A.2). For the whole region, extreme dry events caused, on average, 14 % and 25 % lower soybean and maize production respectively ($P < 0.05$; Fig. 4a,b), whereas extreme wet events enhanced, on average, 14 % and 17 % soybean and maize production respectively ($P < 0.05$; Fig. 4a,c). For instance, wet conditions in 2018/19 enabled the Pampas region to reach its grain production record (33 and 30 Mt of soybean and maize, respectively). Conversely, an 8 % and 10 % reduction in soybean and maize production, respectively, were observed under extreme flood events ($P < 0.05$; Fig. 4a,d), with marked negative impacts in the Pampas periphery (Fig. A.2). Regarding the sown area, results did not show any significant variations either during extreme dry ($P > 0.05$; Fig. 3e,f) or wet events ($P > 0.05$; Fig. 4e,g) in comparison with normal years. The sown area only suffered the effects of extreme flood events, showing, on average, a 6 % reduction for both dominant crops in comparison with normal years

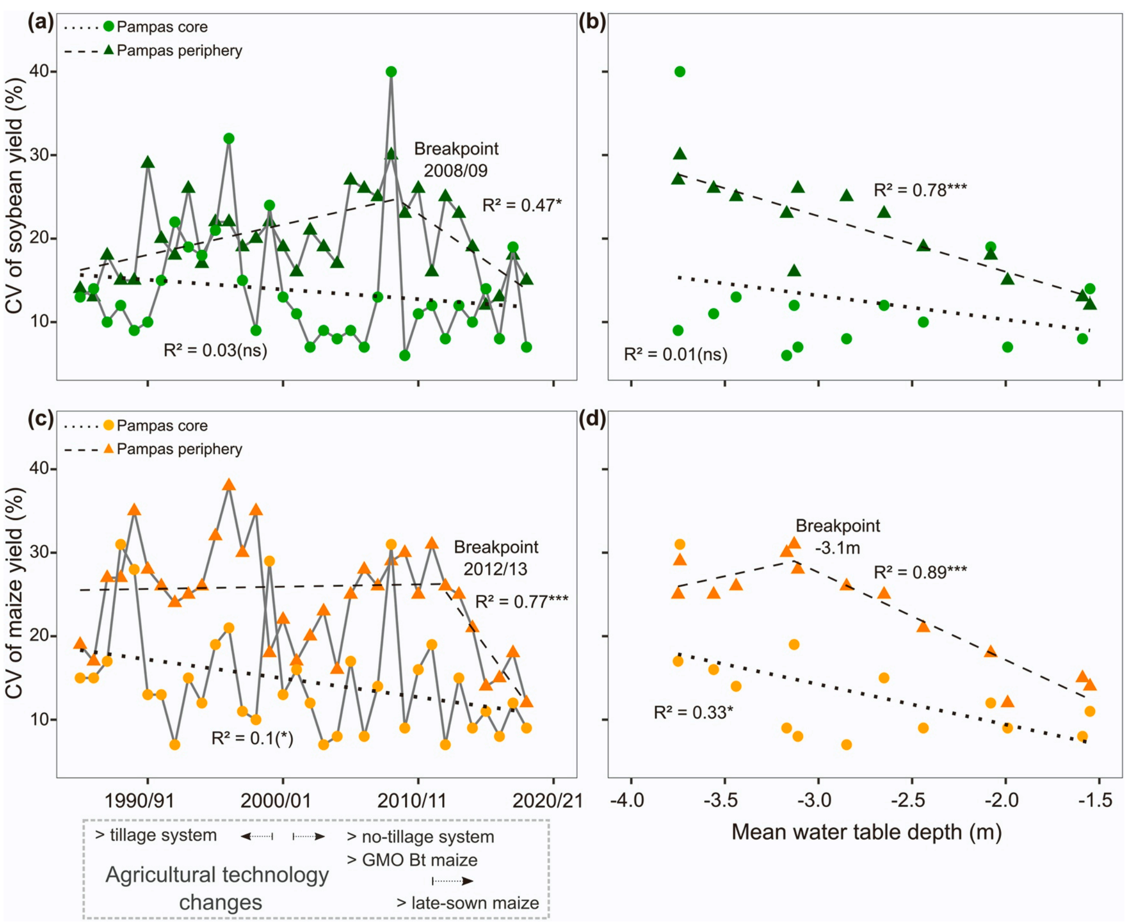

Fig. 3. Relationship between the coefficient of variation (CV) of soybean (green and dark-green) and maize (orange and dark-orange) and the time period 1985–2019 (a and c), and the fluctuation of mean water table depth over the time period 2005–2019 (b and d) in the Argentine Pampas core (circle) and periphery (triangle). Dotted lines (Pampas core) and dashed lines (Pampas periphery) are the best-fit curves of linear regression models and segmented regression models (also known as broken-line regression models). Each symbol indicates the CV of yield for a particular season. R^2 is the coefficient of determination and the asterisks indicate the significance [(*) $P = 0.05$; * $P < 0.05$; * ** $P < 0.001$]. Letters ns indicate non-significant results. Examples of agricultural technology events that occurred during the analyzed years are shown below panel c. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

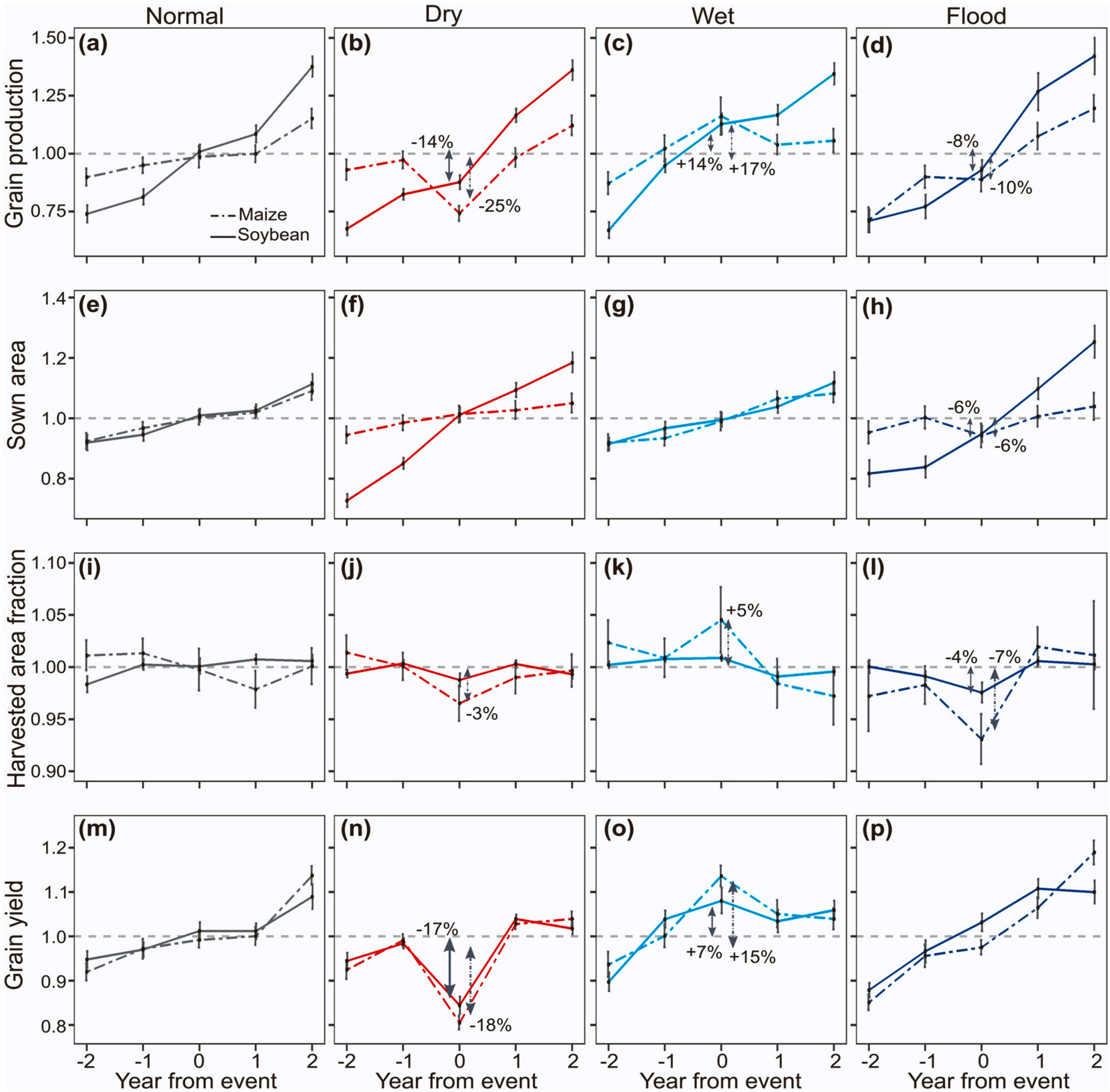

Fig. 4. Variation in normalized grain production (a–d) and its components (namely, sown area, e-h; harvested area fraction calculated as harvested area/sown area, i-l; and yield, m-p) of soybean (solid lines) and maize (two-dash lines) for normal years (dark gray) and extreme dry (red), wet (light blue) and flood events (blue) over 5-year windows centered on the focal extreme event (0). Dots and bars refer to the mean values and 95 % confidence intervals per year, respectively. The solid and two-dash arrows (soybean and maize, respectively) indicate significant differences ($P < 0.05$) in normalized variables between zero year (0) of normal years (a, e, i, m) and zero year of each dry (b, f, j, n), wet (c, g, k, o) and flood (d, h, l, p) extreme events (Table A4); and positive and negative percentages indicate higher and lower changes in those comparisons. The gray dashed lines indicate normalized variable = 1. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

($P < 0.05$). The fraction of sown area that was harvested was sensitive to extreme dry, wet, and floods events (Fig. 4i,j,k,l). On average, the harvested area fraction decreased 3 % in maize cultivated lands ($P < 0.05$), but not in soybean ones, caused by dry events (Fig. 4i,j), and this reduction reached an average of 4 % in soybean and 7 % in maize caused by flood events ($P < 0.05$; Fig. 4i,l). In contrast, extreme wet events increased, on average, 5 % the harvested area fraction of maize ($P < 0.05$), while soybean response was neutral ($P > 0.05$; Fig. 4i,k). The negative and positive responses were always higher in maize cultivated in the Pampas periphery than in the Pampas core (Fig. A.2j,k,l). It is worth mentioning that the absolute mean values of harvested area fraction of both crops (i.e., harvested area/ sown area) over 1985–2019 were always less than the unit, showing that harvested area was always lower than the sown area independently of the specific season weather. Meanwhile, soybean and maize yields were negatively affected by dry events, declining up to an average of 17 % and 18 %, respectively ($P < 0.05$; Fig. 4 m,n). On average, soybean and maize yields had 7 % and 15 % higher values, respectively, during extreme wet events (Fig. 4 m,o), and both crop yields were not affected by floods ($P > 0.05$; Fig. 4 m,p).

The yield response of soybean and maize to growing season precipitation anomaly in counties with and without water table accessibility for these crops (threshold assumed at 3 m of depth) showed a wide range of possible effects from extreme dry conditions to extreme wet conditions (Fig. 5). Yield loss of soybean and maize caused by dry conditions (anomaly <0) was almost double in counties without water table accessibility for crops than in those with it. Relative to their yield trend, soybean yield was reduced ($P < 0.05$), on average, – 11.2 and – 5.9 %, without and with water table accessibility, respectively, while maize yield was reduced ($P < 0.001$), on average, – 14.6 and –7.7 %, without and with water table accessibility, respectively (inset figures in Fig. 5). Under extreme drought conditions (anomaly from –1.5 to –2) in the whole region, the damage was quadrupled in soybean when crops had not access to water table compared to shallow groundwater conditions, reducing soybean yield by an average of – 30.3 and – 7.7 % in each condition, respectively. To a lesser extent, maize yield loss was declined, on average, – 23.8 and – 7.6 % without and with water table accessibility, respectively. Particularly in the Pampas core, soybean yield loss was reduced, on average, – 9,5 % with water below 3 m of depth and – 1.1 % with shallower water tables, increasing up to 9-fold the differences in yield loss between levels of groundwater (Fig. A.3). This buffering effect of shallow water tables on crop yield fluctuations under dry conditions (anomaly <0) seems to have increased during the recent years (from 2015 to 2019) in the whole region, reducing more the yield loss in soybean and maize (Fig. A.4). This last period coincided with the highest peak of groundwater levels in the Pampas (Fig. 1c), which extended the area with water table close to the crop roots zone, encompassing up to 59 % of the counties compared to 34 % at the beginning of the second half of the study period. For example, the last extreme drought (2017/18) caused a mean yield loss of – 26 % (–936 ± 294 kg ha^{-1}) in soybean and – 20 % (–1885 ± 326 kg ha^{-1}) in maize, while a previous extreme drought (2008/09) with similar summer precipitation deficits, but with deeper water tables, reached negative mean values of – 45 % (–1387 ± 598 kg ha^{-1}) and – 34 % (–2497 ± 1167 kg ha^{-1}) in soybean and maize, respectively (Figs. A.5 and A.6). Noticeably, the water tables deepened during the summer of 2017/18 at a rate twice that of 2008/09 (Fig. A.5c,d).

Contrary, the positive yield change did not significantly differ between water table levels in the whole region when precipitation deviated toward wetter conditions (anomaly >0) neither in soybean nor in maize ($P > 0.05$; inset figures in Fig. 5), although yield changes reached negative values in maize under extreme wet conditions (anomaly >1.5). The aforementioned lack of difference was recorded even after seasons that combined wet conditions and flooding episodes (Figs. 1 and 5). However, when we analyzed the yield response to precipitation anomalies in each Pampas subregion, we found that in the Pampas core the positive response of maize to wet conditions was significantly lower (7-fold) when this crop had access to the water table (Fig. A.3c).

4. Discussion

Over the last three decades the Pampas became a key contributor to

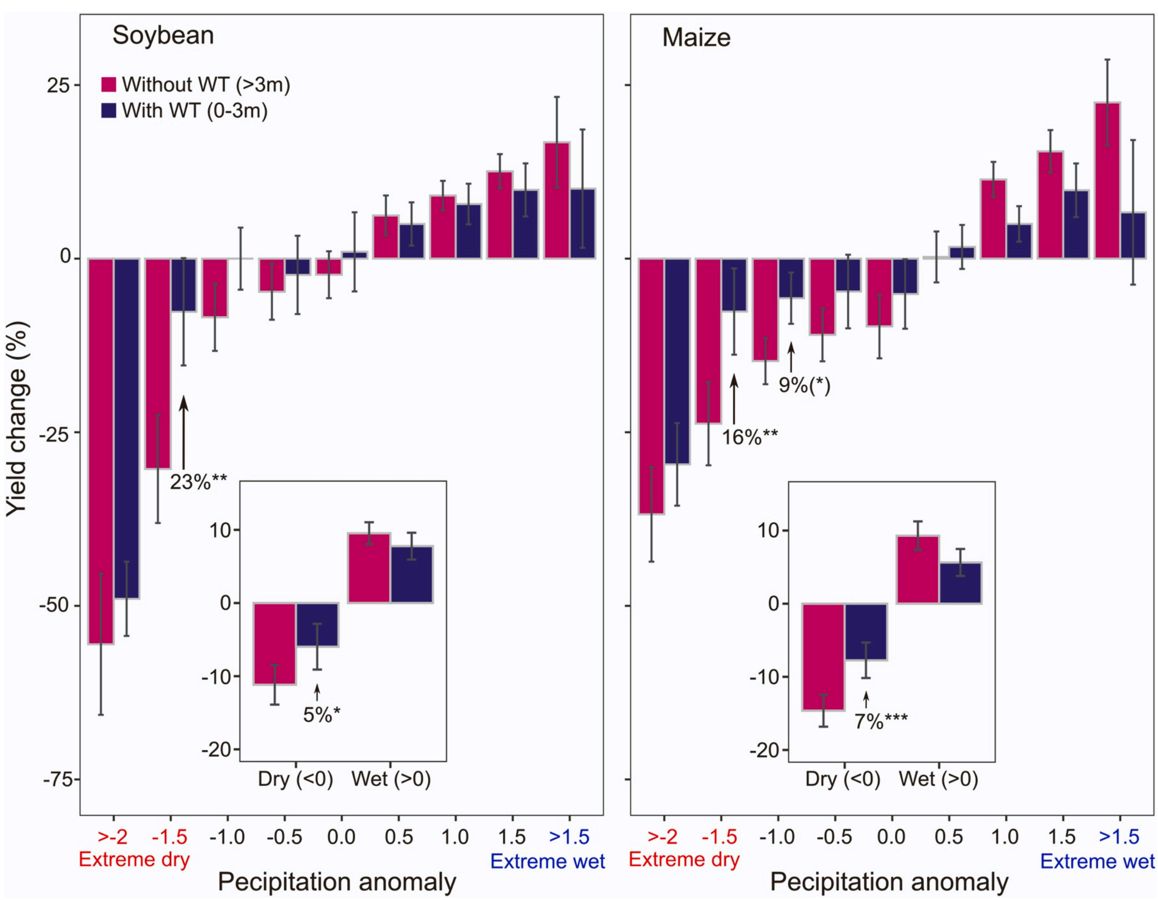

Fig. 5. Soybean and maize yield change response to precipitation anomaly in counties with and without water table accessibility for these crops from 2005/06–2018/19 seasons. Each bar (mean and its 95 % confidence interval) shows the yield change in the corresponding precipitation anomaly range of counties with water table (threshold assumed at 3 m of depth; violet bars) and without water table (depth >3 m; blue bars). Inset figures refer to yield change response to all dry (precipitation anomaly <0) and wet (precipitation anomaly >0) seasons. Yield change was calculated as the yield anomaly divided by the expected yield from their long-term trend. Value and direction (gray arrow) of yield change are shown when they are significant [(*) $P = 0.06$; * $P < 0.05$; * * $P < 0.01$; * ** $P < 0.001$]. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

the expansion of global grain consumption, thanks to a 5.9-fold and 3.3-fold increase in soybean and maize production, respectively (Fig. 2). Following a continental trend shared with more tropical regions like the Cerrado in Brazil and the Chaco in Argentina, Paraguay, and Bolivia (Aguiar et al., 2020; Pereira et al., 2012; FAOSTAT, 2019), higher production in the Pampas relied on area expansion and yield increases in the two main crops, slightly different from the global pattern showing that cropland expansion contributed far less than aggregate yields (Blomqvist et al., 2020). In the Pampas, the sharp area expansion (i.e., almost 3-fold) was supported by the replacement of traditional crops (e.g., sunflower), perennial pastures, and wooded patches, particularly towards drier zones of the periphery, incorporating, for example, five million hectares (i.e., 19-fold increase) of new lands allocated to soybean (Fig. A.1). Interestingly, this replacement has been associated with water table rises in the region with direct effects on the farming system (Nosetto et al., 2015). Currently, regional agricultural expansion seems to be reaching a plateau (Fig. 2c), suggesting that available agricultural land under modern technologies is reaching a limit, overcame at the national level with the ongoing crop expansion over deforested areas of the Chaco region (Piquer-Rodríguez et al., 2018).

In contrast with the plateauing of sown area, soybean and maize yields are still growing in the Pampas, even when farming has expanded towards more marginal lands in the periphery (Fig. 2 and A.1), characterized by lower rainfall and soils with coarser textures and lower water holding capacity (INTA-SAGyP, 1990). Absolute yield comparisons between grain belts highlighted that while in the long term (1969–2019) the soybean yield gains of the Pampas region match those observed in the US grain belt (approximately 30 kg ha^{-1} yr^{-1}), in the specific period analyzed here, which included the fastest expansion rates and hydrological changes, yield gains in the Pampas almost doubled those of the US (approximately 50 kg ha^{-1} yr^{-1}). Nonetheless, maize yields in the Pampas are significantly lower than in similar zones of the US (Zipper et al., 2016). Maize yield increases achieved a pace of up to 210 kg ha^{-1} yr^{-1} at the beginning of the 2000s with a subsequent slowdown, coinciding with large-scale adoption of late-sowing strategies in the Pampas (farmers targeting lower yield potential but higher yield stability under drought; Gambin et al., 2016).

Agricultural expansion and yield increase, mainly explained by genetic (de Felipe et al., 2016) and agronomic improvements (Aapresid, 2019), was accompanied by increasing yield variability in soybean and less so in maize, in partial support to our first alternative hypothesis of growing variability with expansion into more marginal environments in the regional periphery (Fig. 3). Nonetheless, yield variability of soybean and maize began to decrease sharply in the periphery over recent years (Fig. 3), reaching values comparable with other temperate and highly irrigated production systems like in North America (Fig. A.7). Remarkably, these reductions in yield variability took place without an increase in precipitation in the last decade in the study area neither a significant contribution of irrigation (< 2 % of farmlands use irrigation, INDEC, 2019), although the period was accompanied by agricultural technology changes related to management practices (Fig. 3). Our findings suggest that the widespread and progressive water table rise up to a level accessible to crops (Alsina et al., 2020) are also contributing to increase absolute yields, as reported in previous findings for soybean and maize at paddock scale (Nosetto et al., 2009; Vitantonio-Mazzini et al., 2020), and at the same time reduced its variability under rainfed conditions (Fig. 3). This supports our second alternative hypothesis of hydrological buffering. Therefore, a positive interaction between better agronomic management (e.g., massive no-tillage adoption, increasing maize-soybean rotation, delayed maize sowing date) and shallower water table may have led to higher and more stable yields. A recent study in North America attributed the upward trend in maize yield to more favorable weather and management practices in the last decades rather than improvement in genetic, although groundwater contribution was not taken into account (Rizzo et al., 2022). Yield in the drier edge of the Pampas, for example, experienced a sharp increase for soybean and maize, duplicated their magnitude and also reduced their variability over the last decade (Fig. A.8), which suggests that both groundwater and improved management practices may be effective in reducing the yield gaps in a highly water-limited setting (Aramburu Merlos et al., 2015).

While three of the world's largest grain-producing plains (i.e., west of North America, Indo-Gangetic Plain, and north of China) display concerns about entering a new hydrological status of unprecedented groundwater depletion (Famiglietti, 2014; Scanlon et al., 2005), we found the opposite in the Pampas. As water tables raised throughout the second half of the study period flooding become more frequent and widespread, yet a positive effect on yields during drought was detected, with counties with shallow water-tables (<3 m depth) halving yield cuts during dry years, even quadrupling the buffer effect during the driest conditions (Figs. 5, A.3 and A.4). Accordingly, shallower water tables are buffering soybean and maize yield losses at regional scale, partially compensating the lack of artificial irrigation. In the US, the lower drought impact on maize across the drier areas in relation to wetter ones is attributed to the irrigation practices in those driest regions, showing lower sensitivity to rainfall deficiency (Li et al., 2019). Surprisingly, a similar pattern was also found in the Pampas during the last extreme drought in 2017/18 in comparison with the previous ones (Fig. A.9). The yield losses decreased toward counties that accumulated less precipitation but had accessible water tables (depth between 0 and 3 m), suggesting that when the water table is at the optimal depth the influence of precipitation is irrelevant and high yields are observed even without average or higher than average precipitations (Florio et al., 2014). Based on the long-term yield trends in the Pampas, we estimated that the contributions of groundwater to crops during the 2017/18 drought would have allowed an extra production per hectare of 9 % (273 kg ha^{-1}) and 5 % (414 kg ha^{-1}) for soybean and maize respectively (0.9 Mt and 2.2 Mt of total production, respectively), which would have been lost without access to this groundwater resource (Fig. A.6; Table A.4). All these benefits of groundwater supply for crops during dry conditions are maximized in sandy areas of the Pampas (Nosetto et al., 2009) where the poor unsaturated water storage capacity of soils may be overcompensated by their very high saturated storage space (Vitantonio-Mazzini et al., 2021). Paddocks under these conditions with optimum groundwater depth (1.2–2.45 m) had yields that were 3 and 1.8 times larger than those where the water table was below 4 m for maize, and soybean, respectively (Nosetto et al., 2009).

Contrary to shallow water table benefits on crops under dry conditions, negative effects occurred when water table rises caused floods and waterlogging episodes in the Pampas. Under water excess conditions, the production was reduced by a decrease in sown and effective harvested area, leaving soybean and maize regional yields unaffected (Fig. 4), suggesting that these events might impact more the logistics of agricultural operations (e.g., farmers decide to leave areas with low expected yield or cannot even access paddocks) rather than the performance of cultivated plants. However, the response of maize yield seems to show negative effects in some counties of the Pampas core associated with water table rises (Fig. A.3c). The lack of flood effects on average yields may result from the fact that the portion of farming landscapes located in higher positions compensate the yield losses of waterlogged lowlands (Thornton et al., 2014). While the Pampas did not experience the development of artificial drainage networks (e.g., tile drains), this technology is still expanding in North America (1 % annual increase in cultivated lands; Zulauf and Brown, 2019) and encompasses more than one third of the croplands in the northern and central US regions (e.g., 53 % in Iowa; USDA-NASS, 2019). There, soybean yield is 4–8 % higher in artificially drained lands in comparison with naturally drained ones (Mourtzinis et al., 2021). Accordingly, the complex interplay between crop production and water excesses needs better understanding in the Argentine Pampas, where the new hydrological status reflects more cultivated land with water tables closer to the surface (Figs. 1 and 5).

The link between production and hydrological shifts that we documented in our work is relevant not only for farming systems in the Argentine Pampas but those in other sedimentary plains with little irrigation and drainage infrastructure such as Ukraine and Eastern Siberia (Jobbágy et al., 2008; Potapov et al., 2022). With a broader perspective, our results suggest that projections of global food security should account for farming-induced hydrological shifts in sedimentary plains and their likely interaction with climate change. Paradoxically, being almost devoid of irrigation and drainage infrastructure, this grain belt of South America is currently matching the interannual stability of production observed under the more irrigated and drained conditions of North America. Nonetheless, we recognize that other variables besides precipitation, such as temperature and atmospheric CO_2 concentration, along with better management practices may have affected yield gains and production stability (Rizzo et al., 2022). In this sense, our findings of how hydrological changes reduce the sensitivity of grain production to climate may guide further multi-approach studies that analyze the relative contribution to production stability of climatic, hydrological, genetic and agronomic factors. New agricultural adaptation strategies will be needed in the Argentine Pampas in the context of current regional sown area saturation, shallower water table conditions, and higher climate variability. Atmospheric models hint wetter weather, particularly in summers (Huang et al., 2016; Vera et al., 2006), coexisting with extreme dry periods related to ENSO variability (Jozami et al., 2018; Rivera and Penalba, 2015). Accordingly, the region requires sustainable intensification with the challenge of meeting food demand in a climate-changing world, minimizing the pressure for further conversion of natural ecosystems to croplands (Cassman, Grassini, 2020). Three different, but complementary, strategies might be adopted: (1) the implementation of artificial drainage in zones with steeper regional slopes warranting water outlets could buffer future flood and waterlogging impacts on the Pampas' crops, particularly in the Pampas core where unprecedented water table rises were recently observed (Rizzo et al., 2018); (2) the use of cover crops to reduce the water excesses now more common in the region; and (3) the expansion of irrigated farmlands, which has proven to be technically feasible in many regions to stabilize crop yields, and in the Pampas would play an additional role contributing to depress water tables.

5. Conclusions

The Argentine Pampas increased almost 3 and 6-fold its soybean and maize production, respectively, over the last three decades as a result of a large expansion in crop area and yield. Through the whole study period, extremely dry or wet years and long-lasting floods had strong effects in the production of both crops. While floods limited sown and harvested area of soybean and maize, droughts reduced the yield of both crops. However, this yield sensitivity to droughts decreased at the end of the study period. While raising water table levels are increasing the extent and frequency of floods, becoming a bigger concern as they increasingly limit an already saturating cultivated area, the overall effect of shallower water tables on the Pampas ́grain production is positive, at least until the present, thanks to the increased buffering of droughts. This balance may change in the future calling for a deeper understanding of the complex relationships between climate fluctuations, hydrological shifts, farming decisions, and crop performance to project and manage grain production in this relevant global grain supplier.

CrediT authorship contribution statement

Juan I. Whitworth-Hulse: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Writing – original draft. **Esteban G. Jobbágy:** Conceptualization, Methodology; Writing – review & editing, Supervision, Validation. **Lucas Borrás:** Writing – review & editing. **Simón E. Alsina:** Data curation. **Javier Houspanossian:** Writing – review & editing. **Marcelo D. Nosetto:** Conceptualization, Methodology, Writing – review & editing, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data of grain production, sown area, harvested area as well as R scripts will be available after acceptance and under the consent of each particular dataset contributors in a non-profit online repository.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108440.

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