The 2017-18 drought in the Argentine Pampas – Impacts on Agriculture

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Key points

- A major drought occurred in late 2017, early 2018 in the Pampas of central-eastern Argentina, a major world breadbasket. The drought was linked to a mild La Niña event and intraseasonal modes of atmospheric variability. Several locations in the Pampas showed historical lows in precipitation during this event. Lack of rainfall was compounded by high temperatures and heat waves during early 2018.
- The drought had large impacts on production and yields of summer crops – maize and soybean. When propagated throughout Argentina's economy, crop losses (about 1550 M USD) had an overall impact three times higher (about 4600 M USD). Impacts on cattle were lower than on previous droughts because of the intensification of production systems, including shifting cattle to feedlots where forage was externally produced. Conservative estimates suggest that Argentina's GNP decreased at least 0.8% due to this drought.
- The main governmental reaction to a drought in Argentina is the declaration of "agricultural emergency." This declaration postpones state and federal taxes, extends loan repayment due dates, and provides immunity against bank foreclosures.
- Multiple drought mitigation actions are possible both by governments (e.g., enabling adoption of insurance instruments and good agronomic practices to add resilience) and by individuals or firms (e.g., modifying land allocation or stocking rates, agronomic management, and marketing strategies). Farm-level responses are effective under weak to moderate droughts, but strong events overwhelm buffering capacity, particularly for small farms.
- The limited knowledge of associations between drought characteristics and the types and magnitudes of likely impacts is a major impediment to proactive drought risk management by public and private sectors. Because of this knowledge gap, it is difficult to define when to issue different levels of warnings or initiate mitigation actions. Despite its critical importance, information on the agricultural impacts of various climate hazards is not collected or recorded in a systematic way in Argentina.
- Responsibilities for drought are dispersed among many Argentine institutions at multiple jurisdictional levels. There is little coordination among institutions to define who does what and when before during and after a drought.
- There is a strong need for innovative involvement of a diverse set of actors (NGOs, farmers, agronomic advisors, and extension agents) to help co-design effective drought information systems.

This case study focuses on the Argentine Pampas, the flat region in central-eastern Argentina that is one of the world's main breadbaskets [1-3]. We follow a strong drought event that developed in the Pampas in late 2017 and early 2018 and had considerable impacts on agricultural production and the Argentine economy at large – this drought was labelled by some as "Argentina's most expensive disaster on record" [4].

1 The Argentine Pampas

The temperate climate, deep fertile soils, and cropping systems of the Pampas have been described by Calviño and Monzón [1], Hall et al. [5], and Satorre [6]. Agricultural practices are mechanized and efficient, with production oriented towards national and global markets. Characteristic crop rotations include maize, soybean, and a wheat-soybean double crop – wheat followed by short-cycle soybean, allowing two harvests in one cycle [7]. A concentration of production has occurred in the Pampas over the last 2-3 decades: the number of active farms has decreased, while the average area cropped by farmers increased [8-11].

Most of the Pampas show an unusual characteristic that has implications for drought vulnerability: an extremely flat topography with regional slopes < 0.1% [12] and poorly developed drainage networks. In such "hyperplains" horizontal evacuation of excess water is constrained, leading to shallow water tables[1] [13]. Shallow groundwater can provide a helpful buffer against drought: if the water table can be reached by crop roots, it may compensate partially or entirely any rainfall deficit [14-16]. That is, this "groundwater subsidy" may stabilize the yields of rainfed crops (and farmers' incomes) if precipitation is insufficient before or during a cropping cycle [17, 18].

1.1 Climate of the Pampas

Field crops in the Pampas are mostly rainfed, thus crop yields and production depend almost exclusively on rainfall amounts before or during the cropping cycle. Annual rainfall varies between 600 and 1000 mm. There are considerable, and largely unpredictable, year to year climate fluctuations that introduce considerable volatility in crop yields. The main source of climate variability from year to year is the El Niño- Southern Oscillation (ENSO) phenomenon [19-21]. ENSO-related changes in the circulation over South America influence transport of tropical moisture into the extra-tropics; these effects modulate the low-level jet east of the Andes that favors or suppresses occurrence of extreme precipitation events [22]. There are marked links between both extreme ENSO phases and precipitation in the Pampas in the austral spring/summer: El Niño events generally are associated with higher median precipitation, whereas La Niña events show markedly lower rainfall and a narrower dispersion of rainfall anomalies [21]. ENSO impacts on agriculture in the Pampas have been extensively documented [23-34]. Other processes that influence the climate of southeastern South America include humidity transport from the Amazon forest to the east, the displacement of the Inter-Tropical Convergence Zone (ITCZ), the position and strength of the south Atlantic anticyclone, and the Antarctic Oscillation [35-38].

In addition to the interannual signal, the Pampas have shown marked decadal climate variability with alternating dry and humid periods [39-42]. A steady increase in annual precipitation (particularly during the warm semester) has been observed since the 1970s [21, 40, 43, 44]. Precipitation trends in this region have been among the largest observed in the 20th century [45]. In the Pampas, annual mean isohyets have a meridional orientation; the annual rainfall decreases mainly from east to west [35]. Consequently, the precipitation increase partly fostered a westward expansion of agriculture [9].

1.2 Recent trends in agricultural systems of the Pampas

The intertwined effects of climatic, technological [7, 46-49], institutional, and economic [50-52] drivers have induced land use changes of an unprecedented rate and scale in the Pampas [53-56]. Agriculture expanded towards formerly drier areas of Argentina, displacing other crops, pastures, and native

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[1] The water table is defined as the top of the water-saturated zone in the soil profile.

grasslands [2, 55, 57-60]. In turn, cattle production was either intensified in feedlots, or displaced to marginal, more fragile environments, e.g., the dry Chaco north of the Pampas [61, 62]. A striking aspect of land use change in the Pampas has been the increasing dominance of soybeans following the mid-1990s introduction of genetically modified, herbicide-tolerant (GM-HT) soybean varieties [11, 63-68]. The widespread adoption of no-tillage and GM soybeans has reduced costs and simplified agronomic management.

Recent changes in land use and production systems resulting from multiple concomitant drivers have had both positive and negative consequences on drought hazard, exposure, and vulnerability in the Pampas. For instance, crop production that developed in previously drier regions partly in response to increased rainfall, may not be sustainable if – as is entirely possible [35] – climate reverts to a drier epoch. A development with important co-benefits for drought resilience is the widespread adoption of no-tillage sowing: over 90% of all cropped area in the Pampas is currently under no tillage [69]. Under no tillage, minimal soil disturbance, together with the fact that the surface is always covered by stubble, increase infiltration and reduce evaporation. In contrast, soybean dominance may have indirectly increased drought vulnerability: multi-year cultivation of soybean for economic reasons, particularly in small farms, has reduced crop rotation – a good practice that enhances soil water availability by increasing soil infiltration, porosity and water holding capacity [60, 65, 70-73]. Moreover, rotations spread out climate risks, as the various crops have different growth cycles and sensitive periods. Furthermore, the dominance of a single commodity (soybean) makes the Pampas much less resilient to climate extremes such as drought or other shocks like market downturns and emerging plagues and diseases [3]. Fortunately, the soybean expansion has slowly begun to revert in response to policy, technological and economic contexts. Over the last 10 years, soybean area decreased from 19-20 M has to about 17 M has and maize area, in turn, increased from 3.5 M has in 2009/10 to about 9 M has in 2018-19; the larger maize area was accompanied by technological advances that doubled production for this crop over the last 4-5 years [74]. An important feature of production systems with implications on drought vulnerability is the land tenure regime: over 60% of Pampas farmland is not owned by those cultivating it [61, 75]. Studies suggest that rented land often is managed differently from owned land [76, 77]: prevailing short-term (one year) leases in the Pampas may limit tenants' adoption of good practices and resilience-building technologies that often involve high upfront costs, multi-year investment and learning.

2 Droughts in the Argentine Pampas

Over the last century, both persistent flood and drought episodes have occurred in the Pampas, undermining agricultural production and livelihoods [78-82]. Minetti et al. [83] identified major 20th century dry events in the Pampas in 1910-11, 1916-17, 1924-25, 1928-29, 1936-37, 1937-38, 1944-45 and 1975-76. Droughts were common during the drier 1930s–1950s [84, 85]: indeed, during the 1930s the Pampas underwent multiyear droughts, soil erosion, and dust storms – just like the Dust Bowl in the U.S. Midwest [41, 86]. The increase in annual precipitation that started in the 1970s apparently reduced the frequency of strong droughts. Minetti et al. [83] also estimated that 20th century droughts showed annual precipitation deficits of 300-600 mm yr^{-1}, or 30-60% below normal values for a region with annual totals in the 600-1200 mm range. Major droughts in the Pampas also were listed by Naumann et al. [87]. Two of the most damaging dry events – besides the 2017-18 event analyzed here – took place in 1988-89 and 2008-09. The 1988-89 event had significant impacts in the economic sector, with losses of 20% in grain production and minimum levels of hydroelectric power generation in north-western Patagonia [88]. The 2008-09 drought was ranked as one of the most severe events in the globe during the past 60 years; at its peak, over half of Argentina was under moderate drought and 20% of the country was under severe drought conditions [87, 89].

Agricultural drought – the focus of this case study – can be characterized by the Standardized Precipitation Index [90] for a temporal scale of 3 months (hereafter, SPI-3). A detailed study of historical droughts in the Pampas between 1961 and 2008 identified 46 events (defined as SPI-3 < -1); these events had a mean duration of approximately 2 months and a mean severity (the average of SPI-3 values throughout a dry event) of about -1.5 [91]. Spatially, dry events were more frequent in the Pampas than elsewhere in Argentina. Longer-lasting droughts in the Pampas occurred in the 1960s and 1970s [91]; longer dry events may trigger various cascading effects.

Projections of short- and long-term drought frequency and average severity suggest that droughts may become more frequent and intense – but of shorter duration – under moderate and high-emission scenarios over southern South America [92]. Recently, Spinoni et al. [93] used an ensemble of high-resolution climate simulations (CORDEX) and also found that more severe and frequent drought events are likely by the end of 21st century, particularly for high-emission scenarios. Compared to a world before anthropogenic climate change, the latest state-of-the-art climate model projections from CMIP6 show robust drying and increases in extreme drought occurrence across many regions by the end of the 21st century, yet the Pampas are an exception to this trend [94].

3 The 2017-18 drought in the Pampas

In this section we describe the onset, evolution, and end of the strong 2017-18 drought in the Pampas. According to Argentina's Met Service, this drought was the result of the combination of mild La Niña conditions during late 2017 and early 2018 and intraseasonal modes of atmospheric variability. Together, these factors reduced the flow of rainfall and humidity over the Pampas during austral spring and summer, fostering the onset and intensification of dry conditions. Fourteen weather stations throughout the Pampas showed historical minima in precipitation accumulated between October 2017 and February 2018. Between December 2017 and May 2018 there were anomalies of mean daily temperature > 1°C across much of the Pampas; these anomalies peaked in April 2018, when anomalies reached > 3°C. Multiple heat waves were observed in various parts of the region between December 2017 and February 2018.

To follow the evolution of the 2017-18 event, we used two drought indices provided by the Drought Information System for southern South America (SISSA, for its Spanish acronym; this institution is discussed below). First, we used maps of drought categories calculated from CHIRPS rainfall estimates [95]. CHIRPS fields are derived from both satellite data and *in situ* observations; they are produced by pentads (periods of 5 days) and are available since 1981 on approximately a 5 x 5 km grid. A non-parametric distribution was fitted [96] to the time series of rainfall anomalies for each cell and pentad, and used to estimate percentile values for each series. These percentiles were then used to assign each grid cell and pentad/year combination to one of six drought categories following the U.S. Drought Monitor [97]. The drought categories range from "not dry" (percentile values > 30) to "exceptional" (percentiles ≤ 2).

Figure 1 shows maps of CHIRPS-derived drought categories for southern South America for three times during the 2017-18 event. The leftmost panel on Figure 1 corresponds to the 3-month period ending on 5 November 2017. At that time, the Pampas were mostly free from drought conditions; instead, moderate to extreme drought conditions were present in the dry Chaco of northern Argentina and western Paraguay. By 5 December 2017 (not shown), dry conditions moved south: moderate drought was detected in northern Córdoba province (the northern end of the Pampas). By mid-December 2017, dry areas occupied large portions of the provinces of Córdoba, Santa Fe, Buenos Aires and northern Entre Ríos (see Figure 2 for locations of these provinces). During January 2018, dry conditions remained, but their spatial extension expanded and contracted. Dryness intensified during February 2018 and by mid-March 2018 (center panel in Figure 1) large areas in the Pampas showed severe, extreme and exceptional conditions. Such conditions persisted during April 2018, until dry areas began to shrink in May 2018. By 10 June 2018 (right panel on Figure 1) most of the Pampas had

Figure 1. Drought categories for southern South America calculated from CHIRPS rainfall anomalies (see text for details). From left to right, the figures correspond to the 3-month periods ending on 5 November 2017, 25 March 2018, and 10 June 2018, respectively.

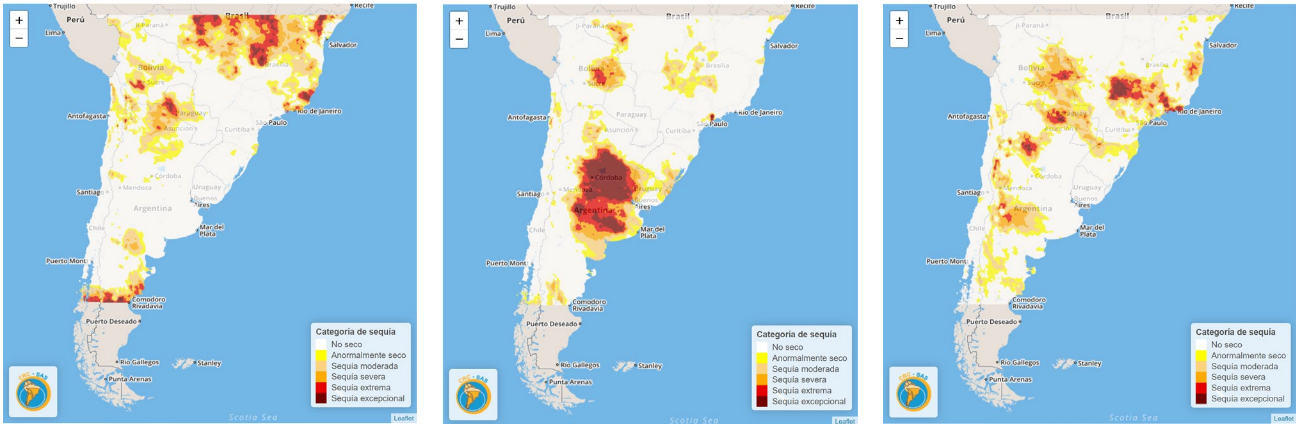
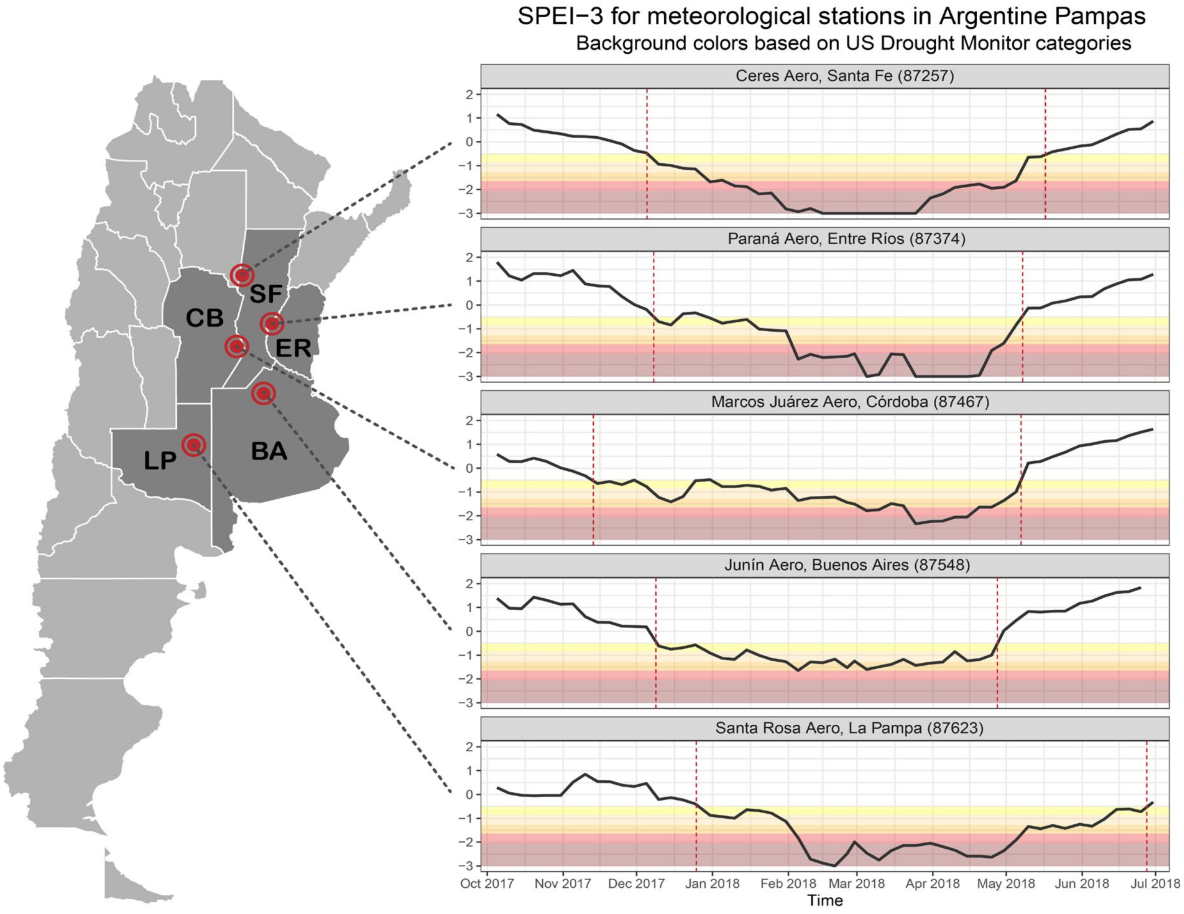


Figure 2. Time series of SPEI-3 values (black line on panels on the right) at five locations in the Pampas. The horizontal stripes in the background indicate the boundaries of drought categories, from moderate to extreme. Dashed lines in the panels indicate the beginning and end of drought conditions in each location (when SPEI-3 values cross the -0.5 threshold). The initials in the map identify the five provinces that make up most of the Pampas region: Santa Fe (SF), Córdoba (CB), Entre Ríos (ER), Buenos Aires (BA) and La Pampa (LP).



returned to non-dry conditions, except for the western edge of Buenos Aires and the eastern portion of La Pampa province.

We also used data the Standardized Precipitation Evaporation Index (SPEI) – that combines precipitation and temperature data [98] – to describe the event of interest. The SPEI was calculated from *in situ* data. Because the high temperatures experienced during this event probably intensified the impacts of low rainfall by increasing atmospheric water demand, the SPEI may be more appropriate than the rainfall-only SPI. SPEI values were calculated six times a month (for dates coinciding with CHIRPS pentads) using a rolling 3-month window. Figure 2 displays time series of SPEI-3 at five locations in the Pampas: Ceres, Marcos Juárez, Junín, Paraná, and Santa Rosa. The SPEI-3 series confirm the evolution described above from CHIRPS drought categories.

Marcos Juárez: This was the first station to show abnormally dry conditions (SPEI-3 < -0.5) around 15 November 2017. Nevertheless, severe drought conditions remained until mid-March 2018, when extreme and exceptional conditions began and lasted until mid-April 2018. Non-dry conditions returned in mid-May 2018.

Ceres: Ceres first showed dry conditions a couple of weeks later than Marcos Juárez, i.e., in the first half of December 2017. SPEI-3 decreased rapidly until extreme drought was reached in early January

2018, such conditions persisted until early May 2018. Conditions returned rapidly to non-dry by mid-May 2018.

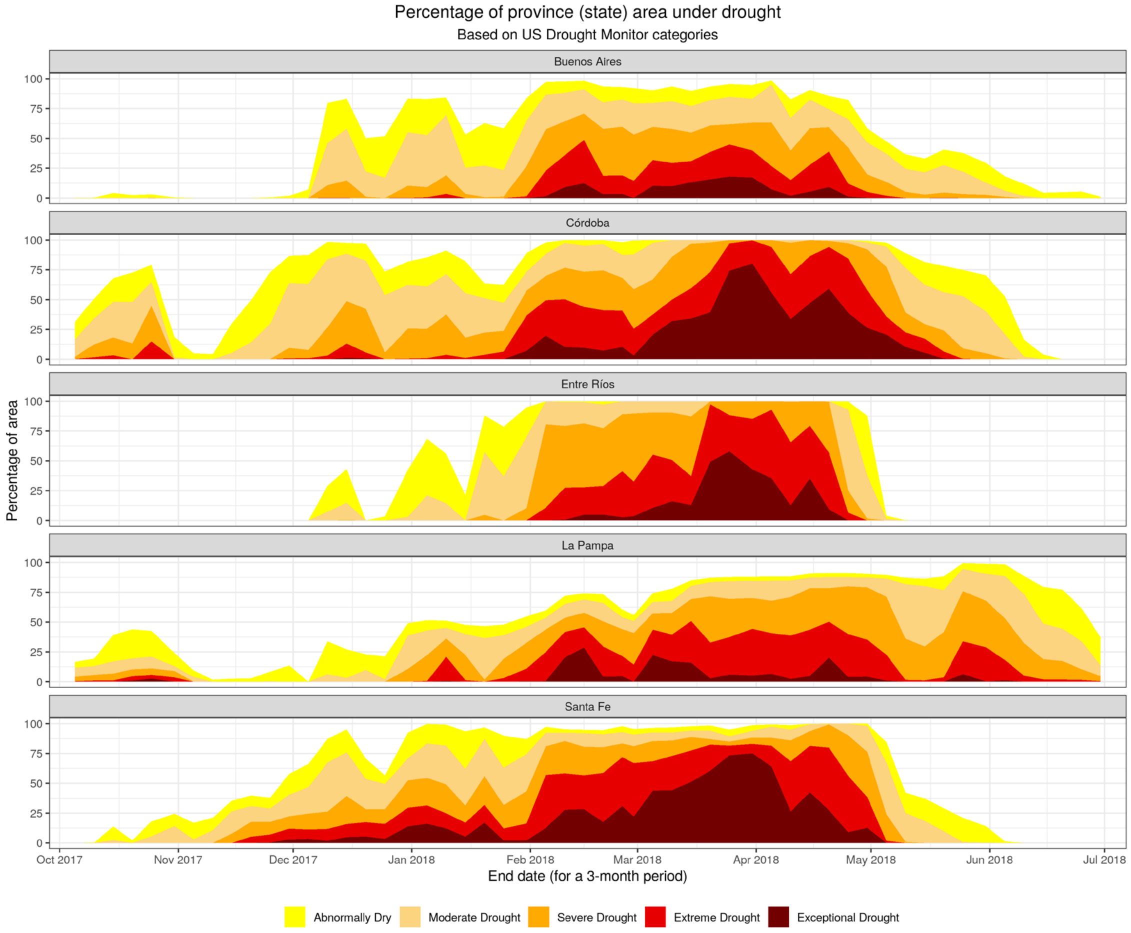
Junín: Abnormally dry conditions started around the first half of December 2017. Between that time and the return to a non-dry situation (in late April 2018) this location never experienced severe or exceptional drought – unlike the other four locations considered.

Paraná: abnormally dry conditions started at about the same time as Ceres and Junín (early December 2017). Between early February and the end of April 2018, this station was under extreme and exceptional drought. During the first half of May 2018, conditions returned rapidly to non-dry.

Santa Rosa: This station – the southernmost – experienced abnormally dry conditions later than the other stations, in the second half of December 2017. During January 2018 conditions intensified slowly to moderate drought, but in early February 2018 the drought worsened quickly, reaching extreme and exceptional categories. Santa Rosa was the last of the locations analyzed to return to non-dry conditions in late June 2018.

Figure 3 shows time series of the proportion of area under each drought category in the five main Argentine provinces of the Pampas. The figure shows that Córdoba (CB, see Figure 2) experienced drought conditions first. Overall, the most intense conditions occurred in the January-April 2018 timeframe. During that time, the provinces of Córdoba and Entre Ríos (ER) were entirely under some

Figure 3. Time series of the proportion of the area of five provinces (states) in the Argentine Pampas under each drought category, from abnormally dry to extreme. The location of the provinces is shown in Figure 2.



drought condition. Santa Fe (SF) and Buenos Aires (BA) did not reach 100% of their area under drought but were close. As described above, La Pampa (LP) showed the longest duration of dry conditions, and almost the entire province was under drought in late May and early June 2018. Analyses of other diagnostics not shown (soil moisture, vegetation indices) reveal subtle differences in drought evolution that are not only associated to rainfall and temperatures but also to soil type and land use.

3.1 Recorded direct and indirect socio-economic impacts of the 2017-18 drought in the Pampas

Summer field crops - maize and soybeans – experienced the largest impacts from the 2017-18 drought. National soybean production (concentrated in the Pampas) was 31% lower in 2017-18 than on both the previous and following cycles. Average soybean yield was 2316 kg ha^{-1}, about 27% and 31% lower than on the previous and following cycles, respectively [74][2]. Short-cycle soybean was most affected, as soil water had been consumed by the preceding crop (wheat) and was not replenished by rainfall during the austral summer [99]. Similarly, national maize production in 2017-18 was 13% and 23% lower than on the previous and following cycles, respectively. Nationally-averaged maize yield was 6088 kg ha^{-1}, 80% and 77% of the previous and following cycles' yields. Because drought conditions were very intense in February-March 2018, most of the lost production (7.5 M tons) was experienced by late-sown maize (for which the sensitive flowering period occurs in those months): average yields were about 6610 and 5300 kg ha^{-1} for early- and late-sown maize, respectively [100].

The impact on farmers' incomes of lower crop production in 2017-18 were partly offset by higher domestic prices tied to decreased supply. Both maize and soybean prices increased about 15% between September-October 2017 and February 2018, when drought conditions intensified. Low production in the Pampas also influenced global markets. Maize prices in the U.S. rose 14% between December 2017 and February 2018, as U.S. exports had to cover the demand that Argentina could not satisfy [4]. In addition, the U.N.'s FAO Food Price Index increased by 1.7% from January to February 2018, to a large extent due to Argentina's drought impact on maize production (http://www.fao.org/worldfoodsituation/foodpricesindex/en/). In contrast, international soybean prices did not rise significantly because of a large harvest in Brazil. Experts pointed out to us that 2017-18 drought-related fluctuations in soybean and maize prices – although very relevant to farmers experiencing that drought – were relatively small in relation to the historical price volatility for these commodities.

The 2017-18 drought lowered Argentina's maize and soybean exports by 4842 M USD (the agricultural sector represents around 60% of total Argentine exports) [99, 100]. Moreover, this dry event was estimated to have induced a 0.2% decrease in Argentina's GDP. This estimate, however, only considers the direct impact of lower crop production and does not include cascading impacts along the supply chain: various published estimates of overall GDP decrease ranged from 0.8 to 3.0% [101, 102].

The 2017-18 drought had considerable impacts on beef production systems – another important export for Argentina, a country known across the globe for the quality of its beef. Extensive beef cattle production in the Pampas is, to a large extent, based on grazing rainfed native and cultivated pastures [103]. Because of dry conditions, grass production estimated through satellite imagery declined steadily from October 2017 to March 2018. By this time, many parts of the Pampas showed unusually low production of pastures and grasslands (near the 5th percentile of the historical distribution, Figure 4) according to Argentina's National Grass Production Observatory (http://produccionforrajes.org.ar/).

Unlike what happened in the region during previous strong droughts in the region, such as the 1988-89 event in Uruguay [104], the 2017-18 event did not cause high cattle mortality or forced sales at low

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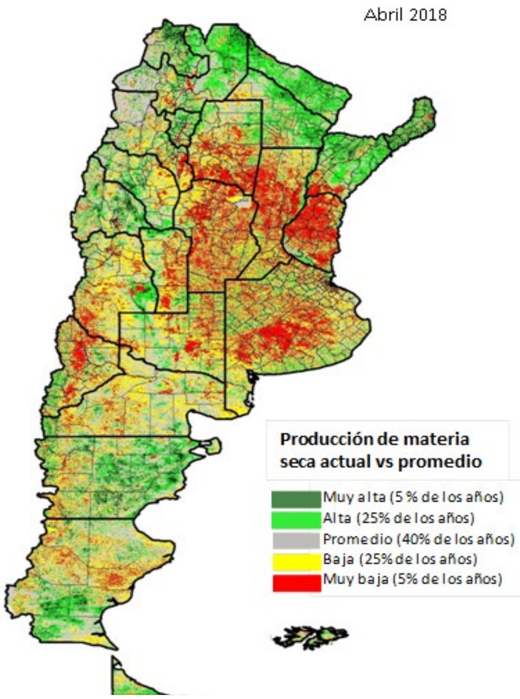
[2] Here we used agricultural statistics from both Argentina's Ministry of Agriculture *(Estimaciones Agrícolas)* and the Buenos Aires Grain Exchange *(Bolsa de Cereales).* Minor discrepancies in yield and production numbers are possible, partly because the Grain Exchange statistics only consider grain that is *traded* – unlike official government statistics that include all production. The discrepancy is not relevant for soybeans, but non-traded production of maize (e.g., grain consumed within a farm to feed cattle) often is much more important.

prices in the Pampas. Slaughter rates increased little; statistics suggest that most cattle sales were to feedlots or finishing farms. The relatively limited impacts on cattle production were in part tied to the growing replacement of pasture-based systems by feedlots. This recent change in production systems indirectly increased resilience against drought – admittedly, despite other potentially negative environmental impacts. Due to the longer timescales of beef production systems, the impacts of a drought may last well beyond the time when rainfall returns to normal. For instance, dry conditions in early fall 2018 delayed implantation of new pastures, decreasing the availability of forage and, therefore, the overall condition of animals and reproductive rates later in 2018. Farmers often are unable to replace cattle lost or sold soon after a drought ends, as they lack capital due to reduced cash flow: recovery, therefore, may take longer than a dry event.

Figure 4. Anomalies of dry matter production in Argentina, April 2018. Red and orange indicate extremely low production, in the lower 5% of the historical record. Source: National Grass Production Observatory.



Dairy production – another important animal production activity in the Pampas – was affected by the 2017-18 drought, but impacts lagged the peak dry conditions. Indeed, in early 2018, i.e., when drought was most intense, milk production increased about 10-20% in the main dairy regions. This counter-intuitive increase may be explained by a couple of reasons. First, the major dairy regions of the Pampas had experienced considerable flooding during the first semester of 2017 [105], thus setting a low baseline to assess year over year production changes in 2018. Moreover, the intensification of dairy production systems – with increased provision of grains and other supplements – prevented a production decrease in early 2018. Nevertheless, delayed negative impacts were experienced in the second half of 2018: the dry conditions experienced earlier that year reduced availability of maize silage.

An aftermath of the 2017-18 drought was the declaration of agricultural emergency (see Section 5.1) in many provinces of the Pampas. Declarations encompassed several productive activities and extended for up to 12 months. The entire province of Entre Ríos (Figure 2) was under emergency early in the event. Emergency was progressively declared for Santa Fe until the full province was covered. Buenos Aires and Córdoba followed a similar strategy: they relied on satellite indices to limit emergency declarations to the most affected areas. The cattle sector in La Pampa was under emergency. Finally, other regions north of the Pampas also were covered by the declarations, although they were not discussed here.

3.2 Cascading and compound impacts, risk of systemic failures

The impacts of drought on agricultural production propagate broadly among other sectors of the economy. For example, each dollar lost in crop production has an impact of three dollars on the Argentine economy due to farmers' lower spending and investment, together with impacts along a crop's supply chain. Direct production losses for maize and soybean in 2017-18 were estimated in 1550 M USD; these losses caused an overall impact of about 4600 M USD to the Argentine economy.

Argentina is currently the leading world exporter of soybean oil and meal[3], and the third global exporter of soy as beans. The huge growth of soybean production triggered private investment in a commensurate processing infrastructure: Argentina has some of the largest processing (crushing) plants in the world [106]. The volume of soybean traded in 2017-18 was about 18 M tons less than originally projected (54 M tons) for that cycle [99]. As about 75% of the soybean production is crushed, in that cycle, processing plants handled about 13.5 M tons less than expected. To avoid idle crushing capacity, Argentina had to increase soybean imports not only from neighboring Paraguay and Bolivia (this is usual), but even from the United States. Many other impacts occurred along the soybean supply chain: Gutiérrez Cabello [107] estimated that about 1200 M USD were lost between the farm gate and the beans reaching processing/export facilities. The largest proportion of these losses (45%) corresponded to transportation costs (an estimated 600,000 truck trips were lost). Cattle and dairy farmers saw their costs increased due to higher prices of maize in 2017-18. We stated above that cattle systems may take a considerable time to recover from a drought because of capital losses (dead or sold animals). If droughts occur often and cash flow is disrupted frequently, there may be a cumulative and possibly irreversible loss of capital that forces cattle and dairy ranchers to exit the activity.

Prolonged dry conditions can trigger cascading impacts on ecosystems of the Pampas. Historically, greater numbers of forest fire declarations are tied to dry conditions (e.g., as in 2004, 2009, 2010, 2011, 2014, 2018). The 2017-18 event showed spatial coincidence between drought-affected areas and areas with reported grassland fires in La Pampa province (Figure 2): 1,164,677 hectares were affected by fire; almost 200,000 heads of cattle were endangered. Buenos Aires province also showed fires but did not declare emergency.

In a tightly inter-connected world, shocks in one or several parts of the system can have widespread ripple effects through global trade networks. Under normal circumstances, the global food system can compensate local climate-related losses through grain storage and trade. For instance, soybean losses due to precipitation in India and Argentina are negatively correlated, therefore losses in India can be likely compensated by imports from Argentina [108]. However, the risk of extreme climatic conditions leading to unusually low global agricultural production can be exacerbated if more than one global 'breadbasket" is exposed at the same time. For example, ENSO has been found to have impacts on yields on all continents that produce crops [109-111]. ENSO impacts on agriculture have been documented not only for the Pampas (Section 2.1), but also for other countries in southeastern South America: ENSO-related variability in year-to-year rainfall influences yields of maize and soybean in southern Brazil [112, 113] and of soybean in eastern Paraguay [114]. ENSO-related shifts in dry spell duration affect maize yields in Uruguay [115]. Moreover, Anderson et al. [33] showed that local ENSO-induced yield anomalies in major producing regions of North and South America − particularly the United States and southeastern South America − are often of the same sign for a given year, which means ENSO poses a correlated risk to crop production in the Americas. In addition to interannual climate variability, global projections of increased water stress over most of the global breadbaskets [116] may pose additional stress on the global food system. Particularly, projected wheat, maize and soybean yield losses in global breadbaskets may see a temperature increase between 1.5 and 2°C [117]. These present and future risks suggest that systemic risks must be considered in a national drought management plan to better cope with external pressures.

4 Existing and/or potential management/mitigation and adaptation options to drought in the Pampas

To organize this discussion, we separately describe actions against drought impacts taken by governmental agencies of various kinds and individual decision-makers (farmers or farm managers). Moreover, considering the trend towards fostering active preparation and planning for drought, rather than simply reacting after a crisis, we separate possible actions into "reactive" and "proactive."

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[3] A crushed soybean produces about 79% meal, 18.5% oil and 2.5% waste and hulls.

4.1 Reactive governmental actions

The main governmental reaction to a drought and other disasters (e.g., floods and fires) with impacts on agricultural production is the declaration of “agricultural emergency.” This declaration postpones (but does not waive!) state and federal taxes, extends loan repayment due dates, and provides immunity against bank foreclosures; in extreme conditions some state-level fees may be waived. Declarations of emergency covering specific regions and periods are issued by the National System for Prevention and Mitigation of Agricultural Emergencies and Disasters, created in 2009. Before benefits are awarded, impacts must be verified by the government – earlier, through on-site inspection; more recently, using satellite data. Although the declaration of emergency is the principal governmental response against drought, consulted farmers stated that the financial impacts of this action are limited and do not contribute significantly to recovering losses. Another component of the agricultural emergencies system is a fund for prevention and mitigation. Unfortunately, the size of this fund (500 M Argentine pesos per year) has not changed since its creation in 2009, therefore its value has been steadily eroded by Argentina’s large inflation. At the time of writing, the annual fund is worth about 7.1 M USD: if this sum were entirely allocated to providing cropping inputs after an emergency, the fund would be able to support about 28,500 ha, or approximately 1/100 of the agricultural area in Argentina.

4.2 Proactive governmental actions

Drought information systems (DISs) can be effective instruments to allow people, communities, and governments to mitigate or reduce the impacts of drought through preparation, improved monitoring and prediction [118, 119]. Often only considered as technical and scientific instruments these systems should empower vulnerable sectors and social groups to mitigate loss and damage. Unfortunately, no coordinated DISs existed in Argentina to help mitigate losses from the 2017-18 drought. Nevertheless, two promising developments have happened: one at the national level, and the other with a broader regional scope. At national-level, Argentina has created the *Sistema Nacional para la Reducción del Riesgo de Desastres y la Protección Civil* (SINAGIR, https://oavv.segemar.gob.ar/sinagir/), an institutional framework for coordination and planning for a broad spectrum of geophysical risks. Within the SINAGIR framework, a network was established linking science and technology institutions linked to the management of various climate and geophysical risks; this network is called GIRCYT, for its Spanish acronym). GIRCYT facilitated the design of an “Interinstitutional Protocol to Manage Information about Meteorological and Agricultural Droughts” in Argentina. In turn, the protocol motivated the formation of a Drought Monitoring Roundtable (DMR) that is playing a crucial role in coordinating the separate, sometimes overlapping efforts of governmental and academic institutions involved with drought. The DMR meets regularly to monitor ongoing and forecasted drought hazard across Argentina. This information, however, is provided mainly to governmental agencies; no broad public dissemination is taking place yet.

At the regional level, the Drought Information System for southern South America (or SISSA, for its Spanish acronym) was launched in 2019. The SISSA is a project operating under the umbrella of the Regional Climate Center for southern South America (RCC-SSA) a six-nation collaboration to produce and disseminate timely, relevant and actionable climate information and services to support decision-making in societal sectors sensitive to climate variability and change. Both the RCC-SSA and SISSA encompass six countries in South America: Argentina, Bolivia, Brazil (south of 10°S), Chile, Paraguay, and Uruguay. In addition to disseminating drought monitoring products derived from *in situ* and satellite data, SISSA aims to address some of the knowledge gaps that still prevent effective preparation for drought, such as enhancing the understanding of associations between drought conditions and the likely regional- and sector-specific impacts.

Upcoming governmental programs seek a more proactive mitigation of the impacts of droughts and other climatic hazards in Argentina. For example, project GIRSAR (Gestión Integral de los Riesgos en el Sector Agroindustrial Rural) is currently in the early stages of operation. Financed through a loan from the International Bank for Reconstruction and Development, GIRSAR will strengthen capabilities needed to manage drought risks in Argentina, including the production and dissemination of agroclimatic information. The project also seeks to promote the development and adoption of financial instruments to transfer climatic and market risks in agricultural production. Simultaneously, Argentina's Agricultural Research Institute (INTA) and academic institutions continue to develop good agronomic practices to reduce risks and stabilize yields and income. A recent development is the increasing role of public-private partnerships in identifying pathways towards resilient agricultural systems: an example is the joint development of HB4 technology to produce drought-tolerant transgenic soybean and wheat.

4.3 Reactive individual actions

Individual decision-makers have important roles in implementing multiple mitigation and recovery actions in response to a drought. In crop production, the spectrum of viable actions depends on when a farmer first becomes aware of an ongoing drought: more choices are available at the beginning of a cropping cycle. At this stage, farmers may clear weeds in fallow land to preserve soil water, modify the planned allocation of land among activities, and/or adjust agronomic management (e.g., genotypes used, planting dates and density). Once a crop is sown, the degrees of freedom decrease substantially. Nevertheless, farmers still may adjust the amount of fertilizer, avoid application of costly fungicides (because diseases are less likely in dry conditions), intensify monitoring of plagues that tend to appear in dry conditions and reduce the thresholds for control of those plagues. Finally, other reactive strategies may involve decisions on when and how to sell the production; use of future markets may be avoided to reduce commitments to production volumes that may not be achieved in dry conditions.

Generally, cattle systems have less options to react to dry conditions. A major option (feasible both before and after a drought is detected) is to reduce stocking rates. In cow-calf systems, early weaning can help. Another option is to move animals to other locations where forage is more abundant. Recently, the option of moving cattle to feedlots (within the same farm or operated by third parties) was used to facilitate supply of feed. Sales once a drought is established should be avoided because prices are likely to be low – everyone is selling cattle simultaneously.

A common reaction by farmers after a drought – both for crop and cattle systems – is to seek financing to replenish working capital. As mentioned, access to bank credit is limited and resisted by farmers because of the historically high inflation rates in Argentina. An increasingly frequent alternative is to seek financing through input suppliers, to be repaid when post-drought crops are harvested. After a very intense drought with significant impact on incomes, some farmers have no option but to sell land or other assets to continue farming; this occurred after the 2008-09 event. Alternatively, some farmers may choose to exit production and rent out their land, usually for a fixed amount (that is, all the risks of production are assumed by the tenant). Government policies should aim to prevent the exit of farmers, particularly smallholders, from active production after extremely damaging droughts, as these actors are unlikely to return to active status [120].

4.4 Proactive individual actions

Micro-level actions by individuals, households, and firms are perceived as the largest – and possibly, the most effective – class of actions against drought in the Pampas. Stakeholders from agriculture's private sector, however, acknowledge that many individual decisions and responses depend on information produced by the public sector (e.g., climate information, technical recommendations from extension systems). Increasingly, farmers in the Pampas are relying on climate diagnostics and seasonal forecasts (together with estimates of available soil water) to make informed decisions. For example, a recent survey of 1000+ members of CREA – a 63-year old Argentine NGO managed by farmers – showed that 50% of farmers consider seasonal climate forecasts when defining land allocation; a larger proportion (over 60%) of farmers use seasonal forecasts to adjust agronomic management. During ENSO extreme phases (El Niño and La Niña events) decision-makers can capitalize on predictions of October-December rainfall – the months for which ENSO effects are most marked – in particular, preparing for the dry conditions that are more likely during La Niña events [26]. Recent awareness of the importance of shallow water tables – typical of hyperplains like the Pampas – has increased interest in the role of groundwater as a "saving account" during dry years. It is now common for farmers to measure water table depth before deciding what to sow. A drought information system that monitors and forecasts the relevant climate variables therefore will play an important role in informing individual production decisions. Nevertheless, farmers or their technical advisors need to be committed and willing to interact with climate scientists to ensure that their information needs are not misunderstood [121].

Recent developments in production systems and management approaches can have significant co-benefits towards drought mitigation – even if not originally developed for that purpose. For example, crop rotation enhances soil water availability, thus helping to buffer against drought, among multiple other benefits [72]. Moreover, rotations spread out climate risks, as the various crops have different growth cycles and sensitive periods. Another development with important co-benefits for drought resilience is the widespread adoption of no-tillage sowing. Minimal soil disturbance, together with the fact that the surface is always covered by stubble, increase infiltration and reduce evaporation.

The recent expansion of late-sown maize in the Pampas was intended to reduce the impacts of precipitation deficits. Maize was traditionally sown in late September and October and flowering occurred in late December or early January, when typically there is less precipitation and high temperatures and solar radiation increase the evaporative demand [122]. By delaying sowing to late November or early December, the yield-critical flowering period is displaced towards February, when both the evaporative demand and the frequency of damaging high temperatures are lower. Moreover, if sowing is delayed until December the soil has more time to accumulate water after the seasonal rainfall intensification in spring; in contrast, maize sown early (shortly after spring rains start) may have less available soil water.

Although cattle ranchers in Argentina have not shown early adoption of technological innovation as much as croppers, beef and dairy production systems are evolving, and some of the observed changes may have implications for drought mitigation. The ability to move cattle into feedlots operated by third parties may increase overall costs for farmers but avoid a significant loss of capital through forced sales or death of animals. With less land devoted to long-term pastures and grasslands in recent years, cattle are fattened increasingly with supplements such as hay, silage, grain, agricultural residues, or directly in feedlots [60]. Intensification of cattle production (i.e., more grain and supplements) makes systems less dependent on grass production and thus less drought sensitive. Most importantly, farmers should actively and continuously monitor grass availability in pasture-based production systems. This assessment should be followed by a proactive, dynamic adjustment of stock size to prevent overgrazing that may lead to cascading effects such as increased soil erosion and, if sustained, desertification processes.

5 Barriers to the adoption of proactive drought risk management – and possible ways to overcome them

Many impediments to react proactively to drought in Argentina are common to several other countries in the region and the world. A simple enumeration of these barriers, therefore, would not provide much new or actionable information. Instead, here we hope to contribute by identifying possible ways to overcome these impediments.

The responsibilities for management of drought risks and impacts are dispersed across several Argentine institutions and multiple jurisdictional levels. Additionally, Argentina lacks specific funding for drought early warning and preparation – these functions are expected to be fulfilled by various governmental institutions (e.g., meteorological, hydrological, and agricultural agencies) as part of their regular activities. This expectation, however, often leads to duplication of activities or, alternatively, to functions that are altogether missing. This issue needs to be addressed through stronger coordination among institutions and well-defined governance. There is a need for clear guidelines – available *before* a drought begins – specifying which institution should do what and at which time, and who should interact with whom. In other words, needed coordination and planning should be explicitly addressed as part of a national drought policy [123, 124]; unfortunately, such policy does not exist (yet!) in

Argentina. The U.N. Convention to Combat Desertification (UNCCD) is currently supporting development of a draft drought policy for Argentina; unfortunately, the document was unavailable at the time of writing. Also, SISSA is currently launching a process to assist countries in the region to develop drought policies and plans.

Drought monitoring and early warning systems are key components of a proactive and integrated drought risk management effort. The Drought Monitoring Roundtable is a positive step in that direction. However, as it evolves and enhances its monitoring, the DMR and other Argentine institutions should not assume that the provision of drought information to policy- and decision-makers will automatically lead to a reduction of impacts from this hazard. There is evidence across the globe that potentially useful climate information frequently goes unused, thus stakeholders are not fully benefiting from services in support of decision-making, risk management and adaptation [115, 125-131]. Understanding why available drought information is not fully used and embraced by decision-makers should be a key priority for monitoring and early warning systems in Argentina and elsewhere [132]. One plausible reason is the lack of expertise in the translation, transfer, and facilitation of the use of drought information among Argentine institutions dealing with this hazard. Moreover, these institutions generally lack effective engagement mechanisms with information intermediaries and end users, hindering sector-specific tailoring of climate information [133].

A major impediment to the adoption of proactive drought risk management by both public and private sectors is the limited knowledge on place- and activity-specific associations between drought characteristics and the types and magnitudes of likely impacts [134, 135]. A good characterization of these associations, however, depends critically on the quality and availability of drought impact data [136]. Unfortunately, information on the agricultural impacts of various climate hazards is not collected or recorded in a systematic way in Argentina. Without relevant information about exposure, socioeconomic contexts, and the related vulnerability of production systems at risk, there are difficulties ranging from the prediction of drought loss and damage to the evaluation of disaster mitigation strategies [137]. There have been attempts coordinated by FAO to harmonize collection of agricultural losses and damages in SE South America, but much work remains to be done. An active network to routinely monitor agricultural impacts of climate hazards should be established by Argentina. Such collaborative network clearly should build on the existing network of observers from the Ministry of Agriculture and extension agents from the Agricultural Research Institute. Nevertheless, the participation of actors from the private sector also should be actively sought, from regional grain dealers and exchanges, to individual farmers who increasingly rely on mobile technologies (e.g., smartphone apps) to both seek and communicate relevant information.

The lack of systematic data on drought impacts also implies that there is no consensus on which drought indices (individual or combined) should be used to monitor agricultural systems and, in particular, what index values should be used as “triggers” that define when to initiate mitigation actions. Related to this, no legal definition of drought or objective criteria for declaration of drought exist so far in Argentina – a problem common to other countries in the region. However, the topic of a formal drought definition is admittedly difficult because criteria should be region- and activity-specific. Drought information systems need to involve the people and communities at risk from drought so they can help to select region- and activity-specific thresholds, indices, or criteria for warnings. Nevertheless, to sustain an ongoing dialog between drought information producers and users can entail high costs for institutions, especially in terms of financial, human, and time resources [138].

Transfer of risks through insurance is globally used to mitigate negative impacts from drought and other climate hazards. Nevertheless, purchase of agricultural insurance is not mandatory in Argentina at present – although there has been much recent discussion arguing that it *should* be. Most crop insurance policies issued in the Pampas focus on damages from hail and other extreme events (freezes, strong winds, fires). In contrast, yield insurance (that would compensate for lower production due to drought) accounts for only about 3.5% of the area insured [139]. A major barrier to broader adoption of crop yield insurance is its perceived high cost. In turn, this cost may be linked to (a) knowledge gaps that prevent construction of an index that is easy to observe and well correlated with impacts, (b) the spatially sparse network of meteorological stations in the Pampas. Farmers question how "representative" of their local conditions (and impacts) may be observations located 30-50 km away – particularly when such observations do not support the claimed local impacts. The observational network is steadily expanding through automatic weather stations maintained by public and private sources (e.g., provincial governments, grain exchanges), but records from these stations are still relatively short (a decade at most) and thus do not allow an appropriate characterization of the drought hazard. Project GIRSAR seeks to gather and harmonize observations from multiple observing networks. In the meantime, drought indices based on satellite-derived data are increasingly supplementing the sparse *in situ* observations.

A feasible proactive governmental action (such as those listed in Section 5.2) would be to boost farmers' adoption of insurance, not only through financial incentives but also through extension and outreach programs to inform farmers about the role of these instruments in mitigating drought economic impacts. Additionally, innovative instruments may be developed to lower the cost of insurance policies. Traditional yield insurance requires on site verification of damages and therefore is expensive. Consequently, there has been much interest from both the public and private sectors on parametric or "index" insurance because these instruments have lower costs (no verification is required). A few insurance companies offer this kind of policies in Argentina, yet they are highly specific (e.g., heat stress on dairy cattle) and their uptake has been limited so far.

Irrigation plays an important role in limiting drought impacts. At present, however, only a small proportion of land in the Pampas is irrigated – with few exceptions such as farms that multiply seeds: only about 170,000 ha of field crops are irrigated in the Pampas [140].The main reason for the limited adoption of irrigation for field crops is the high upfront cost of the equipment in a high-inflation financial context where access to credit is very limited to non-existent. In addition to the initial investment, the operational costs of irrigation equipment (mainly diesel fuel for pumps) are expensive and not perceived to be cost-effective in many areas, even for supplementary irrigation. At the same time, a large proportion of the cropped area is rented, and short contracts prevail, making it difficult to recuperate large structural investments[4]. The current perceptions about irrigation, however, may have to change in light of more frequent droughts, particularly in the semiarid margins of the Pampas that will be most sensitive to increasing dryness [140]. Moreover, if irrigation is to play a role in buffering against precipitation shortages, much basic information will be needed to manage groundwater effectively [141].

Despite the importance of the agricultural sector to Argentina's economy, long-term planning has been limited [50, 142]. Consequently, the evolution of land use and agricultural production technologies in the Pampas have been the emergent result of aggregate decisions by thousands of farmers – influenced mainly by relative profits across competing activities and other contextual factors [9, 143]. Sometimes these emergent patterns have had positive impacts on drought resilience – such as the adoption of no tillage – and sometimes they have not – e.g., a decrease in crop rotations or mixed crop-cattle systems. Unlike other major agricultural countries, in Argentina there are few governmental economic incentives or subsidies that enable farmers' adoption of drought risks transfer and mitigation approaches such as crop insurance and irrigation. Government policies and regulatory frameworks should actively seek to enable good practices and innovations with important co-benefits for increasing the resilience of agricultural systems and transitions to sustainable food production.

The slow and insidious nature of drought – without, in most cases, dramatic impacts apparent to most of the population – is tied to the limited political and public awareness about the recurring issue of drought in Argentina. In turn, this lack of awareness makes it difficult to push for policies that enhance societal resilience to drought (including the agricultural sector). A sustained outreach effort is needed to inform political authorities at all levels (federal, state, and municipal) about drought and the need to plan and prepare to reduce impacts. To motivate governmental action, rigorous evidence should be developed about the human and fiscal impacts of this damaging phenomenon. For instance,

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[4] There are farms for lease in the Pampas where irrigation equipment is available. However, lease prices for these farms can be almost twice as high as farms of equivalent quality but without irrigation.

stakeholders suggested that retrospective analyses of drought events and their impacts should be undertaken and disseminated. Nevertheless, showing that drought (or any other climate hazard) has complex and far-ranging impacts is necessary but not sufficient to mobilize public resources: the costs of not preparing adequately – the so-called "costs of inaction" – should be thoroughly documented as well [144, 145].

Coalitions and partnerships involving multiple social actors (e.g., agricultural boundary organizations) should be developed to facilitate public education and increase awareness of drought risks. Drought information systems, therefore, need to develop mechanisms to develop attract private and NGO participation. Effort should be focused on involving boundary institutions that bridge the divide between information producers and information users (policy- and decision-makers). Boundary organizations can play a key role in enhancing and sustaining communication, as it is almost impossible to sustain communication with the approximately 250,000 active farmers in Argentina. Moreover, boundary organizations are key in translating technical and scientific information into more usable forms [130, 146], and mediating conflicts that arise in the boundary spanning process [147, 148].

We have focused on a major drought in the Pampas that had substantial impacts on agricultural production and the Argentine economy at large. However, an issue that was brought up in the course of this study was the need to avoid neglecting what some stakeholders called "sub-clinical" droughts, i.e., described as those which "decrease crop yields by about 10-15%." These moderate events usually are not deeply engraved in the collective memories of farmers, but are experienced relatively often in the Pampas (about 2-3 such events in a 10-year period). Therefore, throughout the years they can have significant cumulative impacts on farmers' incomes and livelihoods. It would be important to assess whether these droughts begin to occur more often than every 3-4 years, because of either natural low-frequency climate variability or anthropogenic changes. Most importantly, the reason for which stakeholders brought mild droughts to our attention is because, in these situations, good agronomic practices and proactive actions by the public and private sectors (such as those described above) have the highest potential to effectively reduce or mitigate impacts. In contrast, if an event of major severity or encompassing a large area occurs, any buffers provided by proactive mitigation actions may be overwhelmed; in these cases, significant impacts may occur and government emergency assistance will be indispensable.

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