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Dynamics of Socioeconomic Exposure, Vulnerability and Impacts of Recent Droughts in Argentina

Gustavo Naumann [1,*], Walter M. Vargas [2], Paulo Barbosa [1], Veit Blauhut [3], Jonathan Spinoni [1] and Jürgen V. Vogt [1]

1 European Commission, Joint Research Centre, 21027 Ispra, Italy; paulo.barbosa@ec.europa.eu (P.B.); jonathan.spinoni@ec.europa.eu (J.S.); juergen.vogt@ec.europa.eu (J.V.V.)
2 Consejo Nacional de Investigaciones Científicas y Técnicas—CONICET, C1428EGA Ciudad Autónoma de Buenos Aires, Argentina; vargas@at.fcen.uba.ar
3 Environmental Hydrological Systems, Albert-Ludwigs-University of Freiburg, 79098 Freiburg im Breisgau, Germany; veit.blauhut@hydrology.uni-freiburg.de
* Correspondence: gustavo.naumann@ec.europa.eu; Tel.: +39-0332-78-5535

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Abstract: During the last 20 years, Argentina experienced several extreme and widespread droughts in many different regions, including the core cropland areas. The most devastating recent events were recorded in the years 2006, 2009 and 2011. Reported impacts of the main events induced losses of more than 4 billion U.S. dollars and more than 1 million persons were reported to be directly or indirectly affected. In this paper, we analyse the drought risk in Argentina, taking into account recent information on drought hazard, exposure and vulnerability. Accordingly, we identified the most severe droughts in Argentina during the 2000–2015 period using a combination of drought hazard indicators and exposure layers. Three main events were identified: (1) during spring 2006 droughts peaked in the northeast of Argentina, (2) in 2009 precipitation deficits indicated a drought epicenter in the central Argentinian plains, and (3) in 2011 the northern Patagonia region experienced a combination of natural disasters due to severe drought conditions and a devastating volcanic eruption. Furthermore, we analysed the dynamics of drought exposure for the population and the main economic sectors affected by municipality, i.e., agriculture and livestock production. Assets exposed to droughts have been identified with several records of drought impacts and declarations of farming emergencies. We show that by combining exposure and vulnerability with drought intensity it is feasible to detect the likelihood of regional impacts in different sectors.

Keywords: drought; impacts; exposure; vulnerability; risk; policy

1. Introduction

Droughts are the result of a deficit or inadequate timing of precipitation over an extended period of time, often combined with high temperatures and increased water demands. Due to its insidious onset, and often long persistence, it is a complex phenomenon that propagates through the hydrological cycle, from meteorological drought to socioeconomic drought [1]. Accordingly, a drought disaster is related to an event that usually results in serious damage to socioeconomic and environmental systems [2]. The intensity of the disaster and its related damages depend on the combination of the drought severity and their spatial extension, the exposed assets in a certain location and their intrinsic vulnerability. Such drought impacts, e.g., on human societies, have been documented for selected case studies and applied to drought risk analyses from regional to global scales [3–7]. As a general result, the studies showed that certain demographic or socioeconomic factors drive the intrinsic vulnerability to drought-related impacts. Since drought risk is region- and sector-specific, however, each thematic investigation requires a specific set of hazard and vulnerability information to better predict drought impacts [8].

Today, a wealth of drought indices to measure drought intensity and duration are available, characterizing meteorological, soil moisture, hydrological or vegetation conditions [9]. Most commonly, simple indicators that are based on precipitation and standardized products (e.g., Standardized Precipitation Index; SPI) are applied for early warning systems [3]. Among them, drought indices that take into account an approximation of the water balance (like the Standardized Precipitation-Evapotranspiration Index; SPEI) have been shown to be good predictors of drought impacts [5,8,10].

The complex interactions between different economic sectors, cascading effects and indirect impacts hamper a quantification of the overall impacts of droughts. While a variety of different impact datasets exist (e.g., EM-DAT; DesInventar), none of them is complete and a direct linkage to the intensity of the natural hazard is often lacking [7]. Hence, efforts like the U.S. Drought Impact Reporter [11] or the European Drought Impact Report Inventory [7] to collect and standardize drought impact reports are valuable in order to display the multifaceted impacts and to analyse their link to the related drought characteristics. Reports of valid drought impacts can be retrieved from a variety of data sources, e.g., the media, official reports and/or scientific papers. In the few publicly available disaster databases, drought disasters are particularly underreported [11]. The general lack of structural damages, combined with an often prolonged drought duration and secondary and long-lasting effects, and the different further drivers that can increase or decrease the effects of drought (such as a heat wave in summer), make it extremely difficult to retrieve correct loss estimates spatially and monetarily. According to [12], droughts account for less than 7% of the total reported losses from natural hazards since 1960, while other sources document an increasing share for droughts [13]. In general, exists a significant gap between reported and real drought damages and losses that hinders a systematic analysis and quantification and that could help to inform the development of adequate drought management plans [12,14]. To be effective, such plans have to be adapted to local or national needs by taking into account the characteristics of the economic sectors and ecosystems potentially affected.

Despite its significant size, Argentina's economy relies greatly on large-scale rainfed agricultural production (7.6% GDP in 2016). Agriculture is a key sector that represents one fourth of Argentinian exports and one of the main sources of foreign currency income [15]. The country was adversely affected by recurrent droughts with impacts at the local and national level [16–18], but also their consequences are likely to affect food prices and availability at the global level [19]. In Argentina, only a fraction of the rural population is actually involved in farming, population relies mostly on markets for food supply. While the percentage of food-insecure persons in the country dropped from a peak of 10.6% after the economic crisis in 2002 to 1% of the total population in 2012, this issue is still a reality for particular vulnerable parts of the population [20]. Drought, however, can pose a significant problem to large-scale market-oriented farmers, who run the risk of cessation of activity in the most extreme case. Their coping capacity depends on the level of their financial resources for buffering production losses. The main mechanisms applied to cope with the drought risk, therefore, are insurance schemes, specific credits and benefits linked to the declaration of farming emergencies [21].

In this paper, we focus on systematically quantifying the drought risk in Argentina i) as a function of long-term hazard, exposure and vulnerability; and ii) dynamically as a combination of changes in drought conditions and the exposed assets. Information on drought impacts was collected from media news, official reports (national and provincial) and entries from the DesInventar disaster loss database. Our results represent a first step towards understanding how patterns of exposure emerge as a result of the interaction between changes in population structure and regional climate variability. Moreover, we discuss how these indices could be linked to reported impacts and public alleviation measures.

2. Materials and Methods

Following [4], we define drought risk in a contextual approach as a function of the natural hazard, the exposed assets and their vulnerability at a given moment. Drought risk can be understood as the probability of harmful consequences or likelihood of losses resulting from interactions between drought hazard, drought exposure and drought vulnerability. These interactions between the three determinants of drought risk can be represented in a mathematical form [22]; Risk = f(Hazard, Exposure, Vulnerability). The scores of local drought risk range on a scale of 0–1, where 0 represents the lowest risk and 1 is associated with the highest risk.

2.1. Drought Hazard

The hazard component is based on the SPEI [23], a standardized drought index that represents different features of the water balance and therefore is also sensitive to the variability and changes in climatic variables other than precipitation. Similar to the Palmer Drought Severity Index, it includes the effects of atmospheric water demand through the reference evapotranspiration, yet it has the advantage of aggregating variables over different time dimensions that allows identifying different drought types and impacts, similar to the SPI [24]. Recent studies evaluated linkages between the accumulation period of drought indices and impacts in various sectors based on empirical data [3,5,25–27]. These indicate that dependencies between drought indices and impacts are sector- and region-specific, with the best overall performance for the case of Europe obtained using the SPEI for a 12-month aggregation period [8].

For the analysis, we defined two classes of drought intensity (moderate and severe) and the thresholds inspired by the fixed thresholds classification as defined in [28]. Hence, moderate drought events are defined as SPEI $\in [-1.0; -1.99]$, which corresponds to a cumulative probability of 15.9%, while a severe drought (SPEI < -2.0) corresponds to a cumulative probability of 2.3%. Estimations of the related variables (precipitation and reference evapotranspiration) needed to compute the SPEI were obtained for the baseline period 1950–2015 using the CRU v.4.01 dataset [29].

2.2. Exposure

Exposure is the presence of people; livelihoods, environmental sectors and resources; infrastructure; or economic, social or cultural assets in places that could be adversely affected by a climate hazard [30]. In this work, we follow the model of drought exposure by [4], represented by agricultural lands, population and livestock distribution as well as water-stressed areas. These four spatially explicit layers are combined using a non-compensatory Data Envelope Analysis (DEA, [4]) to represent the drought exposure. Exposed assets are defined as the outcome of the intersection between climate and exposure information. A drought event was defined for the month and regions with SPEI values under -1 or below. Hence, the measure of exposure is the number of asset-months under drought, i.e., persons, livestock or crop land affected by SPEI below -1. In the following we briefly describe the various layers used.

Global agricultural lands in the year 2000: This data collection represents the proportion of land area used as cropland in the year 2000. Satellite data from MODIS and SPOT-VEGETATION were combined with agricultural inventory data to create this product [31]. The maps showing the extent and intensity of agricultural land use on Earth were compiled on a 5 min $\times$ 5 min latitude-longitude grid cell size.

Global Human Settlement Layer derived data (GHSL, 1 km resolution) was used to account for the population exposed to droughts. The GHSL population estimates (GHS-POP) correspond to the residential population for the year 2015 [32]. Population was consistently disaggregated from census or administrative units to grid cells, informed by the distribution and density of built-up areas as mapped in the GHSL global layer per corresponding period.

Gridded livestock of the world: This data collection provides modelled livestock densities of the world, adjusted to match official national estimates for the reference year of 2005, at a spatial resolution of 3 min of arc (5 × 5 km at the equator). The freely accessible maps are created through the spatial disaggregation of sub-national statistical data based on empirical relationships with environmental variables in similar agro-ecological zones [33].

2.3. Vulnerability

Vulnerability describes the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard [34]. Vulnerability to drought is estimated based on a multidimensional model incorporating social, economic and infrastructural factors. The underlying indicators are generic proxies that reflect the level of quality of different constituents of a civil society. Vulnerability can be conceptualized as determined by two dimensions, sensitivity (S) and adaptive capacity (AC). Sensitivity captures the characteristics of a community that influence its likelihood to experience harm while experiencing a drought event. Adaptive capacity is a function of both asset-based components of a community such as wealth and human capital that help to predict how flexible individuals may be in anticipating, responding to, coping with, and recovering from drought impacts. Here, each factor is characterized by a set of proxy indicators that are generalized at the national and sub-national scales. Fifteen indicators are selected in accordance with the work of [4,35] and substantiated by the vulnerability studies of [36,37]. Vulnerability to drought is computed as a 2-step composite model that derives from the aggregation of proxy indicators representing the economic, social and infrastructural factors of vulnerability at each geographic location, as similar as for the Drought Vulnerability Index [35]. In the first step, indicators for each factor are combined using a Data Envelopment Analysis (DEA) model [38]. In the second step, individual factors resulting from independent DEA analyses are arithmetically aggregated into a composite model of drought vulnerability. Details of the variables and dimensions adopted can be found in [4,35], while the relevant vulnerability proxies are depicted in the Appendix A.

2.4. Impact Information

The impact quantification was primarily based on a literature and media search in various web-based databases, including news outlets, Google Scholar and Scopus. The key terms used during the search were “Drought” OR “Impact” OR “Agriculture” OR “Argentina”. Additionally, several kinds of word combinations were also used to find more references in Spanish and English. First-round screening was done based on a quick review of title, abstract, and keywords in the articles, official reports and news. After the first screening, a set of impact reports for the main drought events were retrieved from several sources: (1) A search in the national and international media was performed, (2) National and provincial official reports regularly published in the “Boletín oficial de la República Argentina” [39] were examined in order to quantify the location and amount of farming emergencies declared due to drought events as well as related measures taken; and (3) Entries from the DesInventar disaster loss database were explored. The DesInventar database contains a historical inventory of disasters for the period 1970–2009. For drought, it captures the temporal behaviour of e.g., affected people, losses expressed in US$, damages in crops or loss of cattle.

3. Results and Discussion

3.1. Regional Drought Risk

This section examines to what extent the concept of drought risk is relevant to understand how droughts adversely affect the population and the crop and livestock production. Drought affects agricultural production through its effects on yields and livestock, while the population is mainly affected through the reduction of freshwater availability and several indirect effects, like changes in food and energy prices, labour productivity, unemployment, etc. Static risk maps, like the one shown in Figure 1 might be useful to target districts or regions that are recurrently affected by droughts and historically are not able to cope with its impacts. An analysis of their particular vulnerability might help to tailor management and adaptation plans.

3.1.1. Drought Hazard

Figure 1 shows the overall hazard, exposure, vulnerability and risk for the country. The drought hazard is described as the frequency of events occurring at different intensities determined from the historical data (1950–2015). Even though droughts can occur everywhere, the most affected regions are the semi-arid Pampa regions, some areas in the humid Pampa, Patagonia and Cuyo. Dry periods in the region often can be linked to the cold phase (La Niña) of the El Niño-Southern Oscillation. The strongest signal is observed at the end of a La Niña event and in the year after [40]. During the recent past, there was a remarkable increase in precipitation over most of subtropical Argentina, especially since 1960. This has favoured agricultural yields and the extension of crop areas into marginal lands in semi-arid regions [41]. Apart from more favourable climate conditions, this extension was possible due to the application of new production technologies and genotypes, the enhanced global food demand, and the increase in grain prices.

3.1.2. Exposure

Exposure is a necessary, but not sufficient, determinant of risk. For similar drought events, similarly exposed areas might experience different impacts according to their levels of development, land-use planning and mitigation measures. Hence, neglecting vulnerability information, such as levels of development, land-use planning and mitigation measures, is insufficient. It is possible to be exposed but not vulnerable; however, it is also necessary to be exposed to be damaged by an extreme event [42]. Similar to the notion of vulnerability, exposure to drought is a multidimensional concept that varies across spatial and temporal scales. In this work, we considered persons, crops and livestock that are located in an area affected by drought hazard to be elements of exposure. According to [43], in Argentina the estimated total population in 2016 was around 44 million, where 3.5 million are considered as rural population. The population is unequally distributed, with about 60% of the population living in the Pampas region (21% of the total area), including 15 million people in Buenos Aires. Agriculture in Argentina provides around 7% of employment, and accounts for nearly 10% of the country's GDP. The total agricultural land in 2015 was 1.48 million km^2. Beef and other types of meat are some of the most important agricultural export products of the country, with a production of nearly 5 million tonnes of meat. According to FAOSTAT, in 2016 the livestock was composed of 52,636,778 cattle, 14,864,321 sheep, 5,119,438 pigs and 4,712,173 goats.

The regions most exposed to adverse drought impacts are mainly located in concordance with the core crop and livestock areas located in central Argentina (Buenos Aires, Córdoba, La Pampa, Santa Fe and Entre Ríos provinces). According to [44], during 2016, Argentina was the 3rd largest world producer of soybeans with 58,799,258 tonnes produced on a total area of 19,504,608 ha and the 4th producer of maize with 39,792,852 tonnes harvested on 5,346,593 ha of land. Regarding the production of cattle, during the same period, the country was the 6th largest producer with a stock of 52,636,778 head, and the 4th largest producer of meat (2,644,000 tonnes). The country is also a main exporter of fruits. Mainly in Patagonia and Cuyo (Mendoza, Rio Negro and Neuquén), the country produced almost 1 million tonnes of pears during 2016, making the country the second largest world producer and the first exporter of this type of fruit.

3.1.3. Vulnerability

Social vulnerability is linked to the level of well-being of individuals, communities and society, economic vulnerability depends on the economic status of individuals and communities, while infrastructural vulnerability is related to the basic infrastructure needed to maintain the production of goods. The social vulnerability to droughts is higher in the northern part of the country due to lacking infrastructure and slow social progress. González [45] stressed a similar pattern of social vulnerability in the country characterized with the historical backwardness in the Northeast and Northwest regions. In the Chaco region, changes in the land use from extensive grazing through mixed farming to industrial-scale soybean production were made possible by a trend of increasing rainfall and changes in public policy in the late 1970s [41,46]. This process reinforced the concentration of lands for industrial-scale production and excluded small farmers. With little access to credits, these traditional farmers have no access to capital for new technologies such as seeded, drought resistant pastures, or irrigation wells. However, during the early 2010s changes in public policies allowed smallholders to regulate land tenure [46]. Notwithstanding the prominent progress observed during recent years (for instance, increases in life expectancy, and a decrease in infant and maternal mortality rates), these regions remain highly vulnerable, mainly during the time of the recurrent economic crisis.

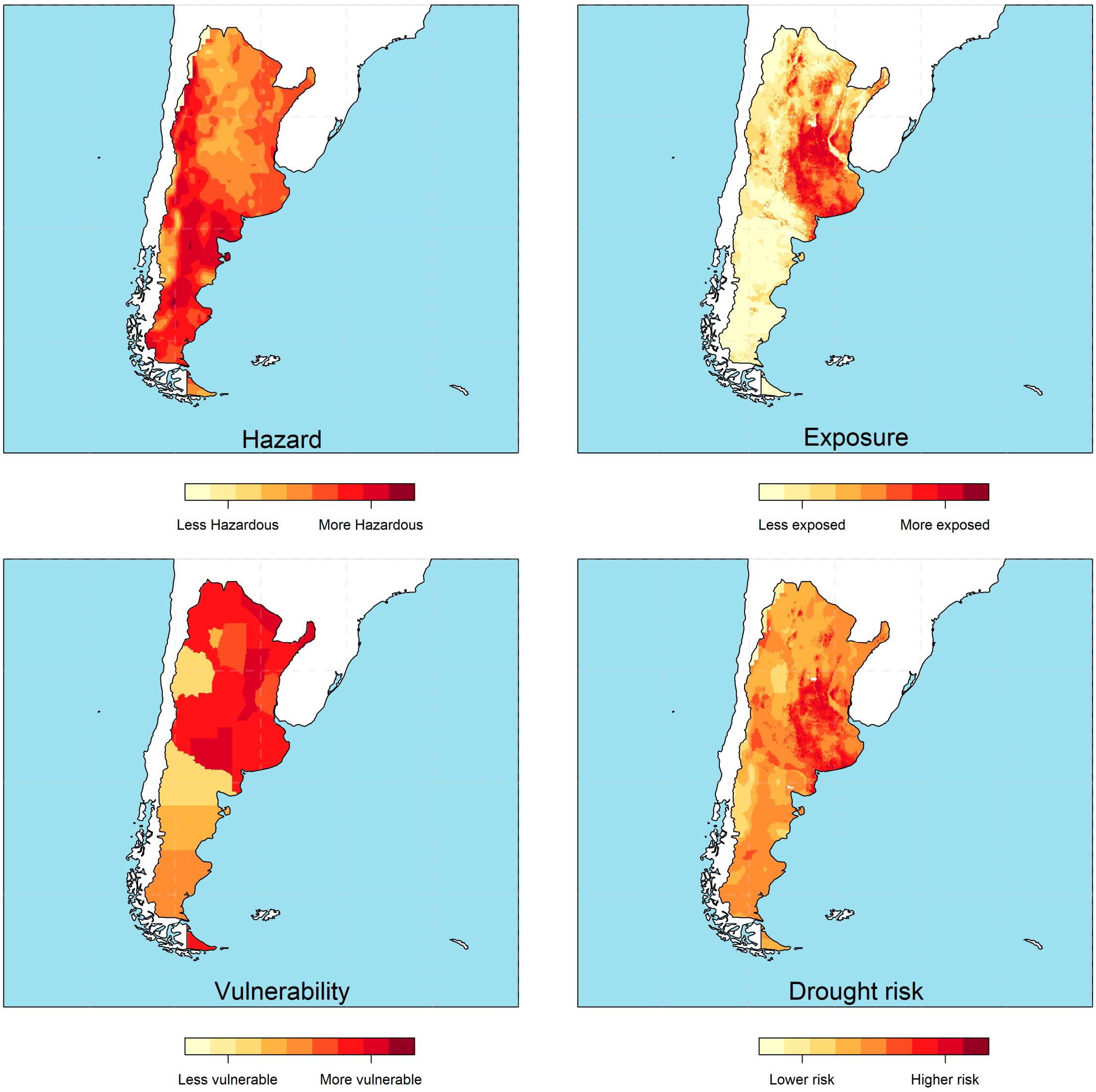

Figure 1. Drought hazard, exposure, vulnerability and the overall drought risk for Argentina.

3.1.4. Risk

As presented in Figure 1, the overall drought risk is lower for remote regions, and higher for populated areas and regions extensively exploited for crop production and livestock farming, such as the Buenos Aires, Córdoba and Santa Fe provinces. Accordingly, regions that have been less exposed are characterized by a lower drought risk. On the areas where there is at least on sector exposed, and as these regions are still subject to severe drought events as well, then their risk increases as a function of the total exposed entities and their lack of coping capacity. As presented in [4], drought risk on the global level is mainly driven by regional exposure, while hazard and vulnerability exhibit a weaker relationship with the geographic distribution of risk values. However, it is important to note that the approach to compute drought risk corresponds to a spatial relative measure and results might change according to changes in the domain or spatial resolution of the data.

3.2. Drought Events, Exposed Assets and Recorded Impacts

As a summary of the drought events observed during the study period, we show the percentage of total land area affected by moderate and severe droughts since the year 2000 (Figure 2). The widest area affected was observed during spring 2009, when more than 50% of the country was affected by a moderate drought and 20% was under severe drought conditions. This event, according to its intensity and extension was ranked as one of the most severe event that occurred in the globe during the past 60 years [47]. Other widespread events were observed during 2000, 2006, and 2011–2012. This trend towards drier conditions is supported also by [48], who detected a significant reduction in the annual precipitation. The authors indicated that during the first decade of the 21st century in Argentina a reduction in the mean annual precipitation of around 200–400 mm was observed centred in Santa Fe, Corrientes, Entre Ríos and Buenos Aires. This reduction is linked to the variability in the equatorial pacific sea surface temperature, but also to changes of the tracks and strength of both, the southern Atlantic and southern Pacific anticyclones.

These dry periods led to impacts in very diverse sectors including agriculture and livestock production but also inland river transportation, hydropower production (Salto Grande Dam located in the Uruguay River reported reductions in the production during the three events), freshwater availability and tourism (Table 1). Even though, the information contained in the media reports could be biased, they represent a fair description and can be extremely comprehensive, and usually similarly reliable as inventories made from official sources [49].

Table 1. Main drought characteristics and impacts of the 2006, 2009, and 2011 droughts in Argentina. Sources detailed in Tables 2, A1 and A2.

	2006–2007	2009–2010	2011–2012
Areas affected	Central and Northeast Argentina	Central Argentina	Central Argentina, Northern Patagonia
Peak month	November	September	September
Maximum area affected	27% of the country	42% of the country	21% of the country
Number of farming Emergencies declared due to droughts and location	32 (in, Central, North East Argentina and Mesopotamia)	53 (in Central, North East, North West and Patagonia)	1 (Northwest)
Main sectors affected	Hydropower, tourism, inland navigation, crops, cattle	Crops, cattle, groundwater, inland navigation, hydropower	Sheep, fresh water availability, hydropower

Table 2. Reported impacts, persons affected and relocated, damages in crops (ha.) and cattle lost during the 2005–2006 and 2008–2009 droughts (Source: Desinventar; http://desinventar.net/).

Event	Reported Impacts	Affected Persons	Relocated	Damages in Crops [ha]	Lost Cattle
2005–2006	36	41,157	0	4,500,000	4000
2008–2009	135	916,500	200	1,050,100	21,280

In many cases, the severity of the impacts led to the declaration of farming emergencies according to law 26.509 [50] (Table A2). One of the main benefits for the producers linked with this regulation is the suspension of the tax obligations until the end of the crop cycle and/or access to low rate credits. To be eligible for the benefits under this law, producers must be affected in their production or production capacity by at least 50%. In that sense, the declaration of a regional emergency is a reliable report of severe impacts as the producers have to proof that the disaster was linked to the respective event. The blue bars in Figure 2 show the number of emergencies declared due to droughts during the period analysed.

As illustrated in [51], during the period 2009–2012, 110 agricultural emergencies were declared in Argentina, out of which 70 were related to drought events. In most of these declared emergencies the farmers were granted with tax reductions or small-scale credits. According to official information (Table A2) during the 2000–2015 period, 118 farming emergencies were declared by provincial or national authorities in response to severe droughts. The 2009–2010 event triggered by far the most emergencies, with 30 declarations in 2009 and 23 in 2010 (Figure 2). During this period, as the drought was widespread around the country, 17 out of 23 provinces declared emergencies. On the other hand, during the 2011–2012 event only one emergency was declared in the province of Salta (Northwestern Argentina).

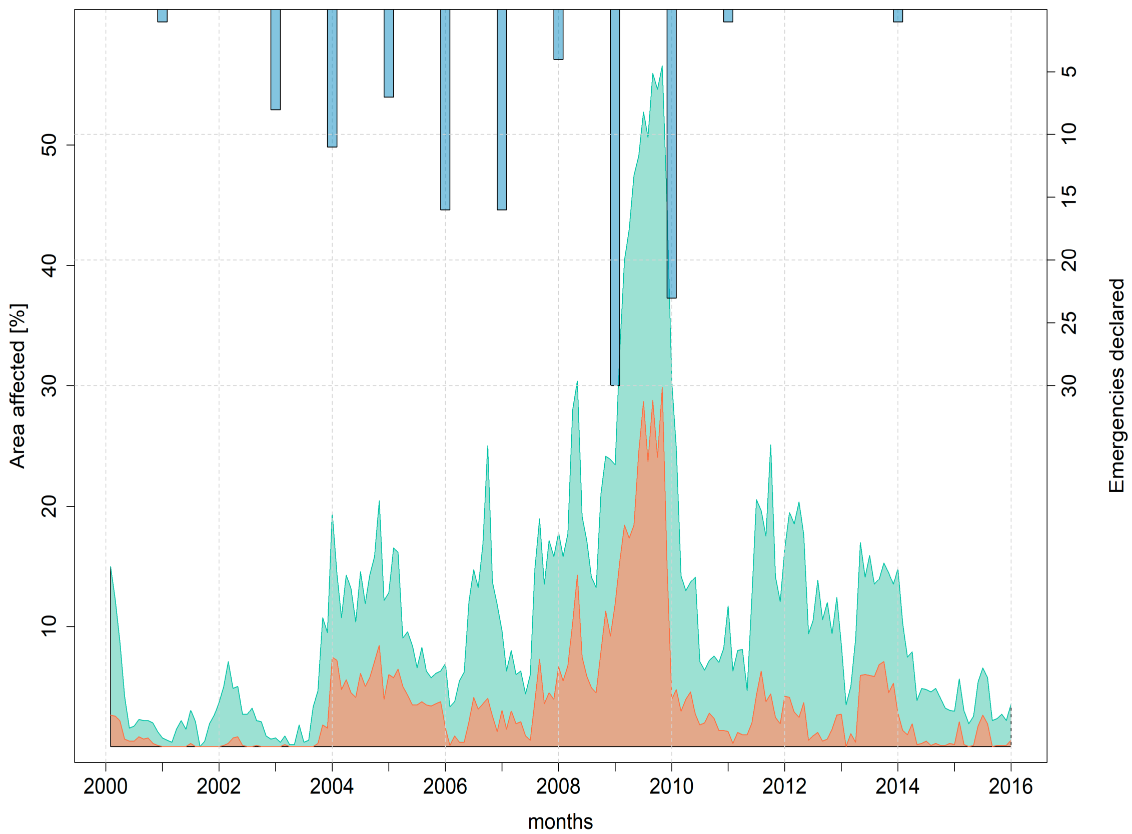

Figure 2. Percent of total land area in Argentina affected by moderate and severe droughts and number of farming emergencies officially declared (blue bars).

Figure 3 shows the spatial distribution of drought severity for the selected events together with the areas that reported impacts or triggered farming emergencies during each period. Overall, there is a good visual match between the most affected areas and the incidence of reported impacts and declaration of emergencies. This is more evident for the 2009 drought, were almost all provinces in the country reported impacts in different sectors.

The dynamic vulnerability and exposure layers are computed for each month. For its computation, the dynamic layer of drought hazard, in this case the monthly SPEI-12 and the structural layers of exposure and vulnerability were taken into account. Figure 4 shows the population, croplands and livestock exposed to droughts for each month together with the main reported impacts during the 2000–2015 period. In addition, in the Tables 1 and 2, summaries of the three main events and related impact statistics and emergency declarations are presented.

As depicted previously, exposed assets were defined as the outcome of the intersection between areas under drought and exposure information. Henceforth, the measure of exposure is the number of assets-months under drought, i.e., persons, livestock or crop land affected represented as the percentage of the total number of exposed assets. When information related to local vulnerability is taken into account (proxies from Table A3) the total number of exposed assets is reduced in proportion of the coping capacity of each region. This reduction is shown in Figure 4 by the broken lines. Even at this relative coarse resolution, the adaptive capacity results in a significant reduction of the total potential assets affected. For instance, during the peak of the 2009 drought, the percentage of population exposed is reduced from 60% to 40% of the total population when adaptation measures are taken into account. Similarly, agriculture and livestock exposed were reduced by about 20% during the same event. This might demonstrate that improvements to the infrastructure like the use of irrigation and/or fertilizers, and improved roads, can lead to a reduction in the overall impacts.

In the following we present a short summary of selected events and related impacts.

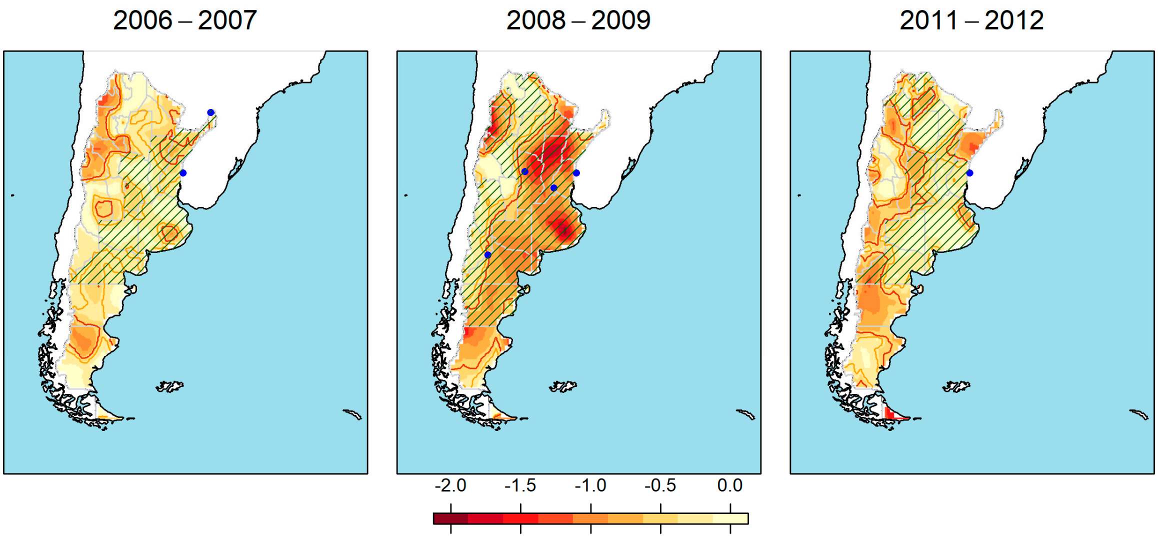

Figure 3. Intensity of drought conditions according to SPEI-12 in Argentina during the events 2006–2007, 2008–2009, and 2011–2012. Orange (red) contours represents the level of severity where at least half year (one year) was affected by a magnitude of SPEI ≤ -1. Hatched lines represent districts were impacts on agriculture and livestock production were reported or emergencies were triggered, while the blue points represent registered hydrological impacts.

3.2.1. 2006–2007 Drought

During this period, drought peaks were centred in central and northeastern Argentina and a prolonged but less intense drought combined with a heat wave affected producers mainly in Buenos Aires, Córdoba, Entre Ríos and Santa Fe. The lack of rain affected mainly maize and soybean production. Losses in the agriculture sector were estimated to around US$2 billion.

Reductions in river discharges were observed in La Plata Basin. Reduction of hydropower generation in Salto Grande Dam located in the Uruguay River and related losses in Buenos Aires of around US$100 million were reported. The reduction in flows from 1500 m^3/s to 350 m^3/s in the

Iguazu falls (Northeastern Argentina) led to the cancelation of several touristic tours producing estimated losses of around US$10 million.

Coincident with these impacts, peaks in exposed population and croplands are evident during spring 2006 (Figure 4). Around 20% of the total population and 30% of the croplands were exposed to moderate droughts.

3.2.2. 2008–2009 Drought

According to Figure 4, during the 2008–2009 event more than half of the total population of Argentina and almost 30% of the agricultural land was affected by a moderate drought. *DesInventar* reported 1 million ha crop damages during the event and almost 1 million persons affected.

More than 40 million head of cattle were exposed to moderate droughts, while 25 million head of cattle were exposed to severe droughts (65% and 40% of total livestock, respectively). According to *DesInventar* entries, 21,280 head of cattle were reported dead. This is the maximum in the analysed period and the third highest loss after the 1989 drought (160,000 head) and 1996 drought (120,000 head). Moreover, media reports stated that around 800,000 head of cattle have been lost [52].

During the 2009 drought farmers called for action to mitigate drought impacts, which are estimated to have caused losses of at least US$4 billion [52]. Among the effects, around 800,000 head of cattle have been lost, while in the Entre Rios province almost 90% of the wheat crop was affected. According to the national weather service, several regions in the country, including the provinces of Buenos Aires, Córdoba, La Pampa and Entre Ríos, were hit by the worst drought since at least 1971. During this period the worst affected area was the Pampas region, where extreme dry conditions were produced by a combination of high evaporative demand and persistent winds.

Significant reductions in the flow rates of the Parana and Uruguay rivers were observed. In Rosario, this prevented the use of small boats, mainly for recreation and forced the international cargo ships to reduce their loads to be able to depart from the port. Some intercontinental cargo ships reported a reduction of their load up to 1.500 tonnes. The most extreme case reported was regarding a cargo ship with 50,000 tonnes of minerals that had to stay in the Port of Rosario for more than one week because the levels of the river were below the minimum depth of water this type of ship can safely navigate. Furthermore, some locations in northeastern Argentina and Paraguay suffered from fuel shortages due to delays in ships transporting these goods from the south, mainly from the Campana and Zárate ports, located in northeastern Buenos Aires.

Starting in 2008, joint droughts affected hydropower generation in the Comahue region and Salto Grande in the Uruguay River forcing to increase the production of electricity from thermal power plants up to 70%. El Chocón was reported to produce energy under minimum flow conditions (140 MW against an installed capacity of 1200 MW with the full reservoir). The minimum of 170 m^3/s was assured to support irrigation and maintain fresh water availability in Neuquén y Río Negro. A shutdown of the hydropower generation was implemented at El Chocón during selected holidays or for specific hours per day to refill the reservoir.

Regarding the persons affected, this is the absolute maximum reported in the DesInventar record (1970–2009). For instance, water restrictions and a low quality of water affected Córdoba City and its surroundings (around 1.5 million inhabitants) due to a deficit of around 1 million m^3 in the San Roque reservoir.

During the period between spring 2008 and the end of 2009, the exposed population, croplands and livestock were more than 40% of the countries' totals (Figure 4). All the observed peaks were related to the reported impacts and declarations of several agricultural emergencies.

3.2.3. 2011–2012 Drought

According to estimates from Argentina's Agro-industry ministry in the eight years starting in 2007, an estimated 1.8 million sheep were lost in Chubut and Río Negro, which is equivalent to 12% of the country's total flock of 14.8 million. These two provinces house 43% of Argentina's sheep population.

During this period, apart from the sheep mortality, the changes in the environmental circumstances promoted by the ash deposits and drought significantly affected Merino wool production and fibre traits in farms of Northwestern Patagonia [53].

During this event, the strongest impacts were recorded in northern Patagonian provinces; however, a longer dry period lasted from 2007 to 2011, when two of the worst droughts in six decades happened [47]. Even if the lack of humidity is recurrent in northern Patagonian provinces, these events were combined with very low summer temperatures and the eruptions of the Chaitén (May 2008) and Puyehue (June 2011) volcanoes.

As represented in Figure 4, during this period the agricultural land exposed to droughts was relatively small and no significant peaks were observed as opposed to the 2005–2006 and 2009–2010 events. However, further noticeable peaks are observed for the population and livestock exposed. All the analysed events presented different areas affected and their linked impacts were accordingly represented by the exposure changes. These changes were verified by a set of impacts reported and the declaration of farming emergencies.

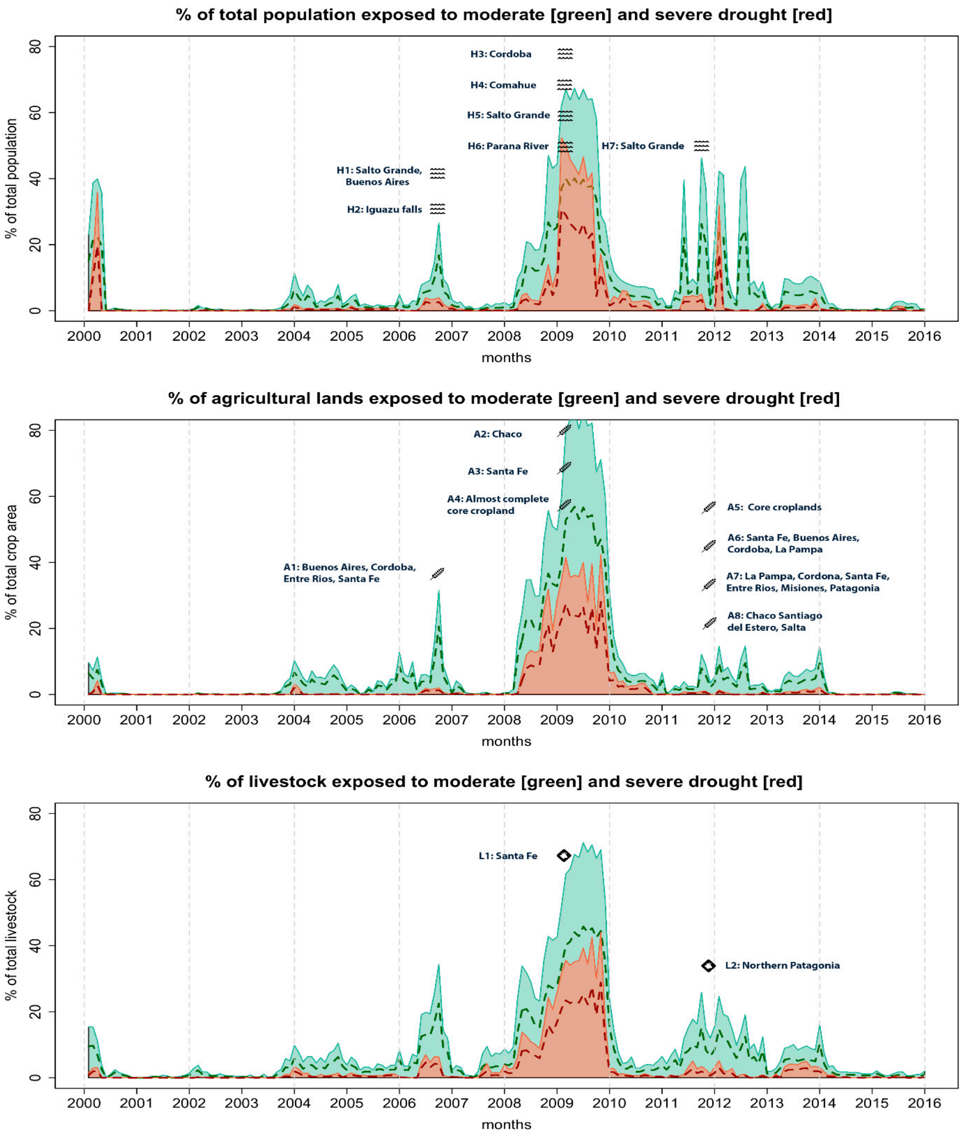

Figure 4. Percent of the total population exposed and hydrological impacts reported; croplands exposed and agricultural impacts reported; and livestock exposed and impacts on livestock reported (period 2000–2015). Dotted lines represent the exposed reduction due to adaptive capacity. Legend abbreviation refers to Appendix A, Table A1.

4. Conclusions

Argentina has committed itself to increasing its food supply to the world, so that it can move from feeding 400 million people in 2015 to 680 million people in 2020, consequently substantially contributing to the achievement of world food security [54]. This increase in food production has to be done under a changing drought risk and thus requires a comprehensive monitoring of drought risk dynamics in order to minimize the related impacts. In the present analysis we explored the sources of drought risk in Argentina by combining recent layers of drought hazard, exposure and vulnerability. According to this information, the key drivers of drought risk for the main economic sectors (i.e., agriculture and livestock production) in Argentina were identified. To do so, the characteristics of the most severe droughts in Argentina during the 2000–2015 period were assessed and their impacts analysed through the incorporation of different information sources (media, official reports, the DesInventar database). The collected impact data enabled for setting up narratives of past drought events that helped us to identify specific sectors that are locally affected by droughts.

During 2006 the drought peaked in the northeast of Argentina, while precipitation deficits indicate the epicenter of the 2009 drought in central Argentina, and in 2011 the most affected areas were observed in the region of Northern Patagonia. The main sectors affected were the ones linked to agriculture (maize, soybean and sunflower production) and livestock production (mainly cattle and sheep). In addition, sectors like hydroelectric power generation, inland water transportation, urban water supply and tourism were severely affected during these events. Impacts in the different sectors became gradually noticeable during the propagation of the drought through the hydrological cycle and due to their interrelations, which led to impacts that are the result of cascading effects and indirect damages. Locally, drought events combined with the exposed assets and the local socioeconomic vulnerabilities (e.g., lack of infrastructure, poverty, etc.), and potentially combined with other natural hazards (e.g., heat waves or volcanic eruptions), can trigger disasters that can affect the economy of the entire country and beyond.

The coincidence of the reported drought peaks and the level of exposed assets was confirmed by documented records of drought impacts and by the number of declared farming emergencies. We could demonstrate that by combining information on exposure and vulnerability with "real-time" drought intensity, it is possible to identify the occurrence of regional impacts across different sectors. This information can be helpful to monitor the probability of impact occurrence from the onset of a drought, or even before, if suitable medium-range forecasts are available. This information is useful to trigger pro-active measures in order to cope with and mitigate the potential impacts of droughts instead of relying on reactive measures to confine the damage when impacts are already manifested and propagated through the entire economic system.

While it is not possible to control the occurrence of droughts, the resulting impacts may be mitigated to a certain degree, namely through appropriate surveillance and management strategies previously agreed and laid out in a Drought Management Plan. These strategies have to be focused on to reduce the local dimensions of vulnerability and increase adaptive capacity.

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Appendix A

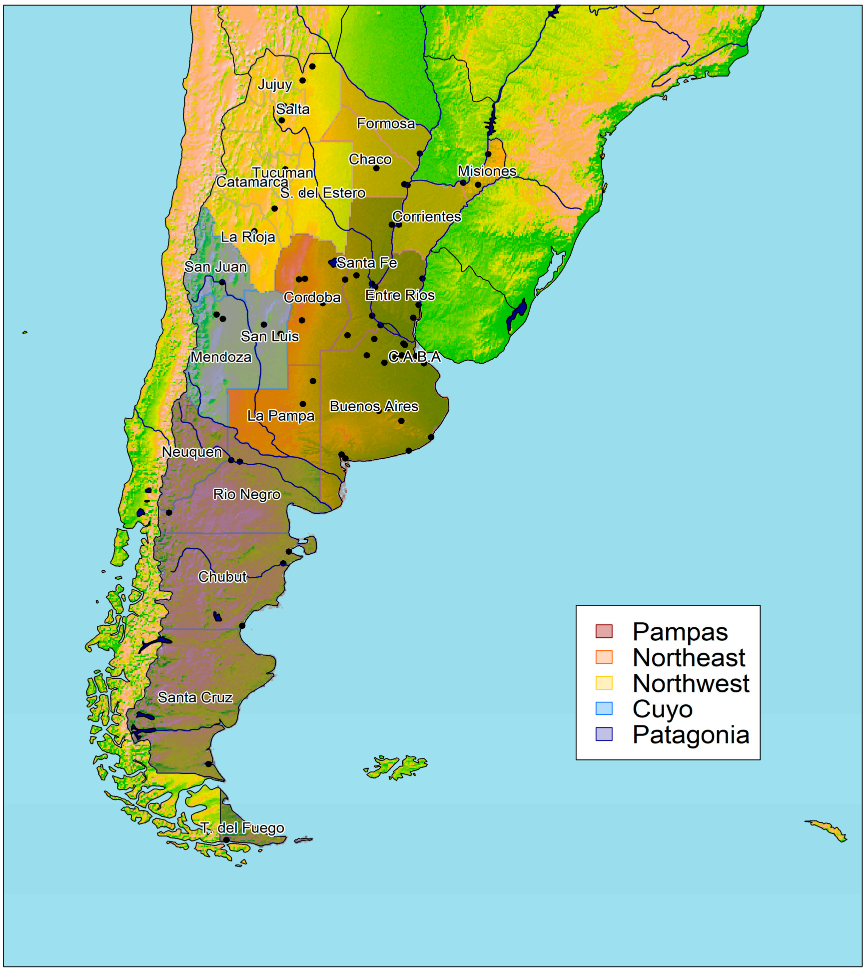

Figure A1. Description of the study area. Digital elevation model, provinces, location of cities with population greater than 50,000 inhabitants and regions used in this study.

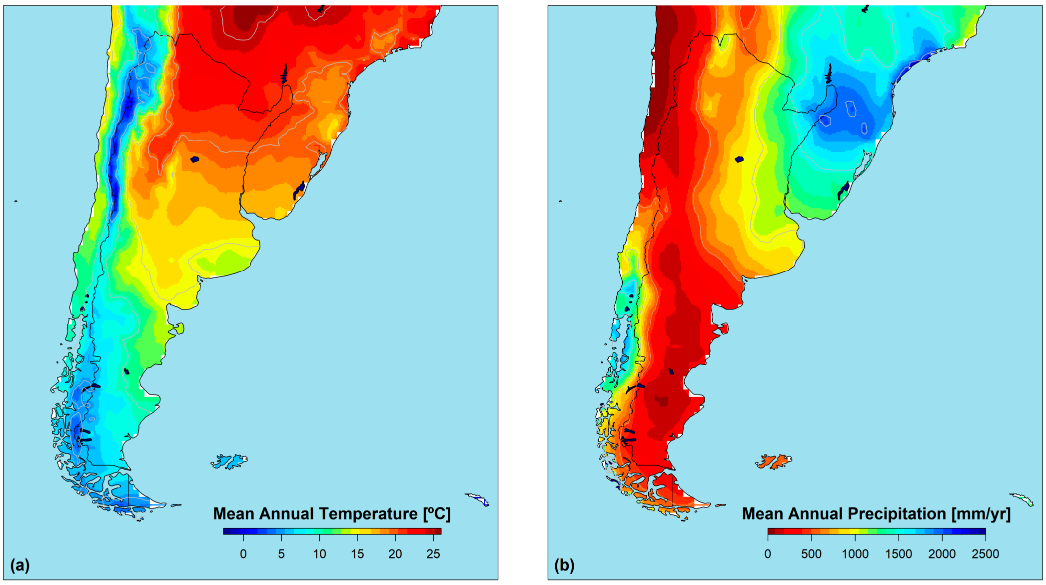

Figure A2. Mean annual temperature (**a**) and mean annual precipitation (**b**) based on CRU v.4.01 dataset.

Table A1. Summary of the selected media reports reviewed in this study. Impacts were classified in three main categories: Agricultural (A), Hydrological (H) and Livestock (L).

Event	Class	Description	Source
2006	**A1**	Estimated losses in the agriculture sector of around US$2 billion. A prolonged drought combined with a heat wave affected producers in Buenos Aires, Córdoba, Entre Ríos and Santa Fe. The lack of rain mainly affected maize and soybean production.	**1**
2006	**H1**	Reduction of hydropower generation in Salto Grande and estimated losses in Buenos Aires of around AR$315 million (circa US$100 million).	**2**
2006	**H2**	Flows reduced in the Iguazu falls from 1.5 million L to 350,000 L. Several touristic tours were cancelled, producing estimated losses of around €10 million.	**3**
2009	**H3** **A2** **A3**	Water restrictions in Córdoba City and surroundings. In Chaco province the area sown with wheat was reduced from 40,000 to 10,000 hectares, while that of sunflower was reduced from 300,000 to 60,000 hectares. In Santa Fe 12,500 farmers were assisted with AR$59 million (US$15 million) and losses were estimated at AR$2 billion (US$0.5 billion)	**4–5**
2009	**A4** **L1**	The drought extends from the southern province of Río Negro through the central provinces of La Pampa and Córdoba and east and north to the provinces of Buenos Aires, Entre Ríos, Santa Fe, Corrientes, Chaco, Formosa and Santiago del Estero. Rural associations estimate that grain production will drop 39 percent and that 1.5 million head of livestock will be lost. In Chaco province agricultural output will be half of precedent year. Corn producers in Entre Ríos estimated losses of over 80 percent. The drought has caused a seven to eight million tonne drop in wheat production, from 16 million tonnes in the last harvest to around eight million with lower levels in 30 years, INTA reported. Estimated losses of at least US$7 billion. In the northern part of the province of Santa Fe alone, 300,000 head of cattle have been lost.	**6**
2009	**H4**	Reductions in hydropower generation in the Comahue region and Salto Grande forced production of up to 70% of electricity from thermal power plants. El Chocón was reported to be producing energy under minimum flow conditions. A shutdown of the electric generation was proposed at El Chocón during selected holidays or for specific hours per day to refill the reservoir.	**7**
2009	**H5**	Significant reduction of the level of the Paraná River near Rosario that prevented to practice any water sport and navigation. Reductions in wheat production and depletion of water reservoirs.	**8**
2009	**H6**	Reductions in the level of the Paraná River. Due to low flows, some intercontinental cargo ships reduced their capacity by 1.500 tonnes. A cargo ship carrying 50,000 tonnes of minerals had to stay in the Port of Rosario for more than one week.	**9**
2011	**A5**	60% of maize production affected in the core zone and a reduction in soybean production was observed.	**10**
2011	**A6**	Due to the severe drought, the government granted AR$3.5 million (US$0.8 million) for small farmers in Santa Fe, Buenos Aires, Córdoba and La Pampa.	**11**
2011	**A7**	Estimations indicated a reduction in 40% maize and around 20% in soybean production.	**12**

Table A1. *Cont.*

Event	Class	Description	Source
2011	**A8**	80% to 90% reduction in soybean production in some areas in the northern provinces (Chaco, Santiago del Estero and Salta).	**13**
2011	**L2**	The current drought in combination with the volcanic ashes produced by the eruption of volcano Puyehue led to the death of around 800,000 sheep in Northern Patagonia.	**14**
2011	**H8**	Salto Grande hydropower production was reduced five times due to the low flows. Only one out of 14 turbines was operational.	**15**

1 http://www.emol.com/noticias/internacional/2006/01/07/207153/ola-de-calor-y-sequia-afecta-a-zona-centro-de-argentina.html. 2 https://www.urgente24.com/138907-sequia-ya-complica-la-generacion-de-energia-en-salto-grande-y-provoca-perdidas-millonarias. 3 https://www.20minutos.es/noticia/145327/0/Iguazu/cataratas/sequia. 4 http://www.elmundo.es/america/2009/11/05/argentina/1257433211.html. 5 https://www.lanacion.com.ar/1089198-la-produccion-agropecuaria-asfixiada-por-la-sequia. 6 http://www.ipsnews.net/2009/01/agriculture-argentina-worst-drought-in-100-years/. 7 http://www.ambito.com/393351-por-la-sequia-se-agrava-la-falta-de-electricidad. 8 http://eleco.com.ar/interes-general/la-peor-sequia-argentina-de-los-ultimos-tiempos-arrasa-con-los-cultivos-y-el-ganado/. 9 https://www.lacapital.com.ar/la-ciudad/por-la-sequiacutea-el-nivel-del-paranaacute-ya-llegoacute-la-peor-bajante-del-antildeo-n309487.html. 10 https://www.infobae.com/2012/01/07/1041682-argentina-enfrenta-la-que-podria-ser-la-peor-sequia-los-ultimos-46-anos/. 11 http://www.univision.com/noticias/noticias-de-latinoamerica/emergencia-por-sequia-en-argentina. 12 http://noticias.universia.com.ar/vida-universitaria/noticia/2012/01/18/905650/sequia-gana-terreno-campo-argentino.html. 13 https://www.americaeconomia.com/negocios-industrias/sequia-arrasa-con-cosecha-de-soja-201112-en-norte-de-argentina. 14 https://www.eldia.com/nota/2011-10-1-la-patagonia-aun-sufre-por-las-cenizas. 15 http://www.informedigital.com.ar/secciones/departamentales/53243-salto-grande-produce-menos-energia-por-la-bajante.htm.

Table A2. Number of farming emergencies declared by provincial and national authorities due to drought events by province and year. Source "Boletín Oficial de la República Argentina" [39].

	Pampas					Northeast					Northwest					Cuyo				Patagonia					
year	**B. Aires**	**Córdoba**	**Santa Fe**	**La Pampa**	**E. Ríos**	**Corrientes**	**Misiones**	**Formosa**	**Chaco**	**Santiago del Estero**	**Salta**	**Tucumán**	**Jujuy**	**La Rioja**	**Catamarca**	**San Juan**	**Mendoza**	**San Luis**	**Neuquén**	**Río Negro**	**Chubut**	**Sta. Cruz**	**T. d Fuego**	**Total**
00																								**0**
01	1																							**1**
02																								**0**
03	3										2	2							1					**8**
04	3	1		1		1						1			1	1	1			1				**11**
05			1				1				2	2		1										**7**
06	4	1	1	1	1	1	2		3	1												1		**16**
07	6		3	1	1	2								1						2				**16**
08			1						1												2			**4**
09	2	1	5	4	3	2			3	3					1				1	3	1	1		**30**
10	3	3	3	3				1	1	1	1			1			2			1	1	2		**23**
11											1													**1**
12																								**0**
13																								**0**
14										1														**1**
15																								**0**

Table A3. Indicators of drought vulnerability in detail: corresponding factors, data sources, reference dates and correlation to the overall vulnerability (negatively correlated indicators are related to adaptive capacity).

Factors	Indicator	Scale	Correlation	Year	Source
Economic	Energy consumption per Capita (Million Btu per person)	Country	Negative	2014	U.S. EIA
	Agriculture (% of GDP)	Country	Positive	2000–2014	World Bank
	GDP per capita (current US$)	Country	Negative	2000–2014	World Bank
	Poverty headcount ratio at $1.25 a day (PPP)	Country	Positive	2000–2014	World Bank
Social	Rural population (% of total population)	Country	Positive	2000–2014	World Bank
	Literacy rate (% of people aged 15 and above)	Country	Negative	2000–2014	World Bank
	Improved water source (% of rural population with access)	Country	Negative	2000–2014	World Bank
	Population ages 15–64 (% of total population)	Country	Negative	2000–2014	World Bank
	Government Effectiveness	Country	Negative	2013	WGI
	Disaster Prevention & Preparedness (US$/Year/capita)	Country	Negative	2014	OECD
Infrastructural	Agricultural irrigated land (% of total agricultural land)	5 arc minute	Negative	2008	FAO
	% of retained renewable water Hydrological	catchment	Negative	2010	Aqueduct
	Road density (km of road per 100 sq. km of land area)	Vector	Negative	2010	gROADSv1

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