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Comparison of adaptative strategies to climate variability in rural areas of Argentine Chaco and US Southern Plains during the last century

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ABSTRACT

Considering uncertainties regarding climate variability, the objective of this study was to make a long-term (1901–2011) comparative assessment of the impact of land-use decision (changes in the cultivated area) and technology adoption as adaptative mechanisms of the rural sector in the Argentine Chaco and the US Southern Plains. Different sources of data on climate (precipitation, minimum, mean and maximum temperature and evapotranspiration), land-use change (proportion of cultivated area) and technology adoption were used. This work involved three main analytical steps: i) Principal Components Analysis (PCA) was applied to identified the dominant components of data variance, ii) the relationship between the residuals of precipitation and land-use change was assessed by means of a simple regression analysis and iii) technology adoption was evaluated through a proxy based on historical changes in the yield of maize (*Zea mays* L.). The results showed that farmers in both countries relied on two common adaptative strategies to face climate perturbations during the study period: i) land-use change (a simple binary decision of planting or not planting in response to climate conditions) during a first stage, and ii) the introduction of adaptative technologies to smooth the impact of climate during the second one. That substitution of adaptative strategies begun during the 1940 decade in the US Southern Plains, and around 30 years later in the Argentine Chaco. The adoption of technologies and agronomic practices explained the sensitivity decay of the cultivated area to the climatic variability during the second stage. The incorporation of improved hybrids with higher drought resistance plus the adoption of tilling practices like minimum tillage or no-till, the input of fertilizers, pesticides and irrigation water (the last one in US, only) became a successful strategy to mitigate the risk of climate perturbation.

1. Introduction

Despite agricultural activities may be well adapted to average climate conditions, they may be highly sensitive to variability and climate extremes (Antle, 2009). During the past decades, the intensity, severity, extent, duration and frequency of unusual climate conditions have had a marked influence on agricultural systems, which range from negative to favourable (Reidsma et al., 2009). In water-limiting environments such as those of the semiarid and sub-humid areas, climate variability normally increases production risks (Meinke and Stone, 2005).

Historically farmers have relied on a few adaptative strategies to face the climatic uncertainty, which have depended on the ability to anticipate climatic hazards. Land-use decisions were the most important strategy to enhance the adaptative capacity of agriculture to climate variability. Because of it, field crop production in most semiarid and sub-humid regions has been a rather opportunistic activity that strongly relied on a favourable climate (Smit and Skinner, 2002). During low-rainfall periods land was allocated to livestock production, while crops were planted when precipitations

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increased (Viglizzo et al., 1997; Wolfe, 2011). As previous research in Argentina (Viglizzo and Roberto, 1989; Hutchinson et al., 1992; Riera and Pereira, 2009; Baldi et al., 2014) and US (Walthall et al., 2012) has demonstrated, an on-farm diversification of activities was a successful strategy to face climate variability in semiarid and sub-humid regions.

More recently, the incorporation of better agronomic practices, management strategies and input-based technologies improved water use efficiency at the field level and reduced the dependence on precipitation (Calviño and Monzon, 2009). Adaptation became more complex and specialized (Antle, 2009). The gradual adoption of minimum and no-tillage, cover-crop management, stubble mulch fallow (Nickerson et al., 2011), crops tolerant to drought (Jackson et al., 2009; Ludwig and Asseng, 2010) and even irrigation in US (Meinke and Stone, 2005; Jackson et al., 2009; Delgado et al., 2011) has played an increasingly relevant role as effective risk-mitigation strategies (Walthall et al., 2012).

Adaptation efforts vary largely among and within regions, depending on the geographic location, economic diversification, institutional capacity, capital availability, infrastructure, technology level and vulnerability to climate extremes (Burton and Lim, 2005; Reidsma et al., 2009, 2010). Because of lacking adaptation technology, semiarid and sub-humid lands in developing countries may be more sensitive to suffer the negative impacts of climate than developed countries, which are better endowed to face climate risk (Smit and Skinner, 2002). We based our research on the idea that regions that had similar legacies from rural colonization and production may eventually show different adaptation strategies in response to different socio-economic, cultural, technological and political conditions.

Most quantitative studies on this topic have focused on exposure and sensitivity, while adaptative capacity have often been focused in a highly simplified way (Reidsma et al., 2010). Few empirical studies have neither undertaken nor quantified the issue of adaptation to climate variability (Maertens and Barrett, 2013). Relying on this view, the objective of this study was to make a comparative assessment of land-use and technology adoption as adaptative strategies to face climate perturbations in the Argentine Chaco and the US Southern Plains, which comprise important semiarid and sub-humid agricultural areas (Rosenzweig et al., 2004).

Our hypothesis was that land-use decision was a powerful adaptation strategy as long as technology was scarce, but that strategy lost importance as the irruption of technology-adaptation options emerged and multiplied across both regions throughout the 20th century. In order to test it, we compared rainfall variability with the proportion of annual crops and maize yield in both regions through the last 110 years. The proportion of annual crops and the maize yield represent, respectively, the land-use and the technology-adaptation strategies that were studied. Considering that the past offers valuable lessons for the future, we aimed in this work at assessing and interpreting how the agricultural sector in both regions have faced the climate risk.

2. Materials and methods

2.1. The study areas

To analyse how has varied the adaptative capacity of agriculture to climate variability across different territories, we applied a cross-continental comparative and quantitative approach using existing databases from diverse sources (Baldi and Jobbágy, 2012). We studied the Argentine Chaco (AR) that has an extension of 232,873 km^2 and the US Southern Plains (US), which extends over 84,879 km^2. Both regions have been subdivided into semiarid (SA) and sub-humid (SH) areas, which were respectively identified as: SA-AR, SH-AR, SA-US and SH-US. We defined the limits of these regions based on the climatic attributes established by UNESCO (2010) in the case of Argentina and USDA/JAWF (1994) for US. For each of these environments, we randomly chose 10 specific sites that cut across various longitude and latitude coordinates. Fig. 1 shows the regions compared.

Table 1 provides the location and area of 40 individual sites used to compare environments through statistical analyses of climate and land-use data.

2.2. Climatic and land-use data sources

Different sources of climatic, land-use/land-cover and technology data were combined in this research.

Climate data came from the reconstruction of historical climate data (1901–2011) produced by the Climate Research Unit (CRU), School of Environmental Sciences, University of East Anglia, UK (Mitchell and Jones, 2005) (http://www.cru.uea.ac.uk/). The CRU dataset includes values on a regular grid interpolated onto a 0.5°, covering the global land surface. These authors used an automated method that included the development of reference series using neighbouring stations. They checked the database for heterogeneities in the station records using incomplete and partially overlapping records. The station anomalies were combined with published normal data. Climate grids are available for ten climate variables: mean temperature (TMP), maximum temperature (TMX), minimum temperature (TMN), precipitation (PP), potential evapotranspiration (PET) diurnal temperature range (DTR), wet-day frequency (WET), frost-day frequency (FRS), vapour pressure (VAP), and cloud cover (CLD) for 1901–2011. The method used by CRU to calculate PET is the FAO (Food and Agricultural Organization) grass reference evapotranspiration equation (Ekström et al., 2007, which is based on Allen et al., 1994). It is a variant of the Penman Monteith method using the gridded TMP, TMN, TMX, VAP and CLD. PET values are mean mm/day, therefore we needed to multiplied them by the number of days for the year to get the mean annual PET. Given the reliable and homogeneous structure, together with the large time period covered by this system, we decided to base our analysis on this data source, using the most relevant climatic variables (TMP, TMX, TMN, PP and PET).

Land-use/land-cover changes (in terms of the proportion of land occupied by annual crops in general) were assessed through the original global land-use dataset provided by Ramankutty and Foley (1999) (http://www.geog.mcgill.ca/~nramankutty/Datasets/Datasets.html). These authors presented an approach to derive geographically-explicit change in global cropland from 1700 to 2007. By calibrating remotely-sensed land-cover classification data against cropland inventory data at the national and subnational scale, Ramankutty and Foley (1998) reconstructed global representation of permanent croplands at 0.5° resolution. By overlaying the historical cropland dataset over a potential natural vegetation cover dataset, Ramankutty and Foley (1998) estimated the extent to which different natural vegetation types were converted to agricultural lands. Likewise, they also estimated the extent to which croplands have been abandoned in different parts of the world. The reconstructed changes in historical cropland were highly consistent with the history of human settlement and patterns of economic development. Those data were used to understand the impact of climate variability on land-use change.

2.3. Estimation of the proxy for technology adoption

To quantify the process of adaptative technology in both countries we used a proxy that indirectly represents technology

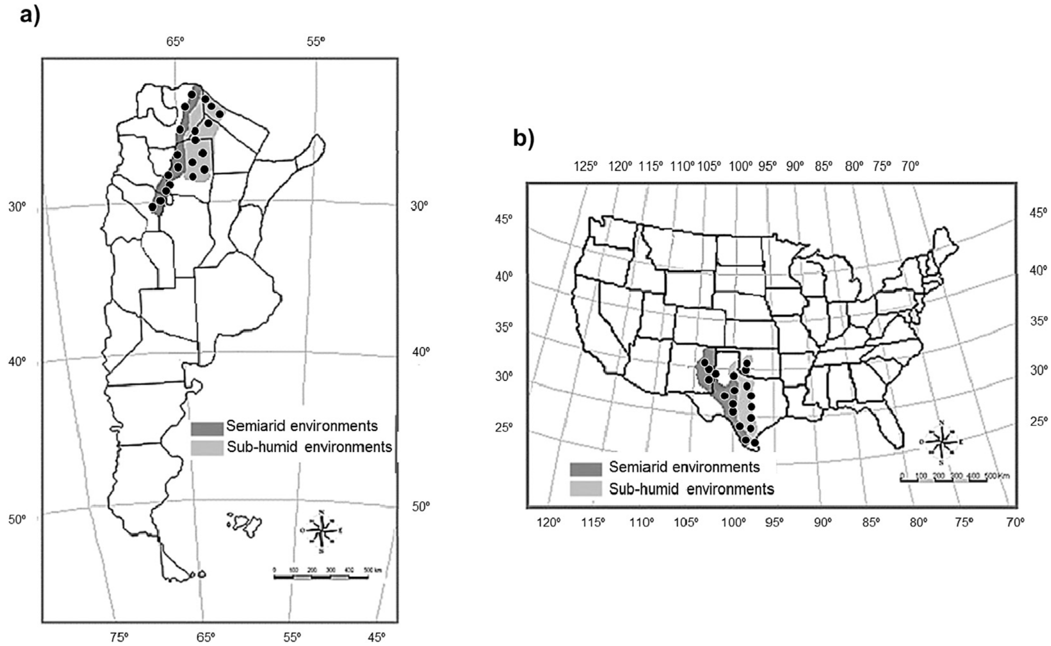

Fig. 1. Location of the study areas and specific sites (points location) References: Grey areas indicate the location of semiarid and sub-humid rural environment of the Argentine Chaco (a) and US Southern Plains (b) and black dots indicate the study sites.

adoption in the mid- and long-term (McWilliams and Zilberman, 1996). Both in Argentina and US, the proxy for technology adoption were calculated from public statistics for annual maize yields covering the period 1901–2011. In the case of Argentina, we used national statistical data from SAGyP (1994) which covered the period 1901–1994 and national statistical records provided by FAO (2013) to complete the remaining study period. In the case of US we used national statistical records of maize yield provided by USDA (2014), which covered the entire period 1901–2011. In order to allow a comparison, the proxy for technology adoption was standardized to vary within a scale that ranged from 0 to 1. The yield corresponding to the figure of 1 represents the highest average yield (10.34 ton/ha) recorded in the US throughout the entire period.

2.4. Data analysis

The work involved three main analytical steps: i) in order to compare and explore the dynamics of climate and land-use change in the study regions, we explored the variance of the dataset by means of Principal Components Analysis (PCA); ii) through a simple regression analysis we estimated the relationship between the residuals (deviations with respect to the average temporal trend) of precipitation and land-use changes (changes in the cultivated area as adaptative factor to climate variability); and iii) relying on proxies for technology adoption in Argentina and US, we evaluated how technology (a more recent adaptative factor) has impacted on the relationship between precipitation and land-use change using anew simple regression analysis.

2.4.1. Identification of the components of variance

By means of PCA (Cooley and Lohnes, 1971), we got a first-order description of the underlying mechanisms that explain the role of land-use change as an adaptative tool to deal with the temporal climate variability. The PCA was focused on the following variables: cultivated area, precipitation, temperature (average, maximum and minimum) and potential evapotranspiration. The components of variance were assessed across three historical periods (1901–30, 1931–60 and 1961–2011) in order to appreciate temporal changes in climate conditions and farming decisions throughout the whole study period. The PCA was performed on those periods considering bibliographic data of Reca (2006). This author mark three technological stages in both countries over the last century: i) a first stage prior to 1930 where technological development in both countries was rather low, ii) a second phase of 1930–1960 where it was expressed a large gap between the US and Argentina incorporated technology, and iii) a third stage from 1960 onwards, where the situation started to change slowly as a result of an extensive effort of modernization of Argentinean agriculture. Thus, the PCA analysis for the semiarid and sub-humid regions of the two countries covered the period 1901–2011 through a three-stage time.

This procedure allowed us ordering further analysis. On one hand, reduced the multidimensional complexity of data to a smaller number of independent variables that account for most of the variance in the original dataset. On the other hand, showed how the variance of climatic and land-use variables disperse and relate across a two dimensional space comprised by axis X (PC 1) and Y (PC 2). Finally, allowed us to prioritize further analytical steps on those variables that showed the highest variance.

Prior to PCA analysis, was performed the standardization of the variables in order to homogenize them and avoid equivocal results due to the disparity among absolute values, units and expressions. Through this process was transformed the distribution of each variable in the dataset $[X \sim N(\mu, \sigma)]$ through $Z = (X - \mu)/\sigma$, where X is the score of each variable, μ is the arithmetic mean of the distribution, and σ is the standard deviation. The new standardized variables have an arithmetic mean equal to zero, and a standard deviation equal to one $[N(0, 1)]$. The statistical software used was The SAS System 9.0 and Statgraphics Plus 5.0.

2.4.2. Response of cultivation decisions to climate variability

According to the results obtained by PCA, we continue the analysis based on changes in precipitation and land-use in both countries during the period 1901–2011. Given that changes in land-

Table 1
Location and predominant size of study sites in the Argentine Chaco and US Southern Plains.

Agro-ecological area	Specific sites	Geographical coordinates		Geographical site	Unit (km^2) department/ county
		Latitude	Longitude		
SA-AR	SA-AR 01	−22.25	−62.75	Santa Victoria (Salta)	3912
	SA-AR 02	−23.25	−63.25	General José de San Martín (Salta)	16,257
	SA-AR 03	−24.75	−63.75	Anta (Salta)	21,945
	SA-AR 04	−26.75	−64.25	Pellegrini (Santiago del Estero)	7330
	SA-AR 05	−27.25	−64.25	Banda (Santiago del Estero)	3597
	SA-AR 06	−28.25	−65.25	Santa Rosa (Catamarca)	1424
	SA-AR 07	−28.75	−65.25	La Paz (Catamarca)	8149
	SA-AR 08	−29.25	−65.75	Capayán (Catamarca)	4284
	SA-AR 09	−29.75	−66.25	Chamical (La Rioja)	5549
	SA-AR 10	−30.25	−66.75	General Ángel V. Peñaloza (La Rioja)	3106
SH-AR	SH-AR 01	−22.75	−61.75	Ramón Lista (Formosa)	3800
	SH-AR 02	−23.25	−61.25	Bermejo (Formosa)	12,850
	SH-AR 03	−23.75	−60.75	Patiño (Formosa)	24,502
	SH-AR 04	−23.25	−63.75	Rivadavia (Salta)	25,951
	SH-AR 05	−24.25	−61.75	General Güemes (Chaco)	25,487
	SH-AR 06	−24.75	−62.75	General Güemes (Chaco)	25,487
	SH-AR 07	−25.25	−62.75	Almirante Brown (Chaco)	17,276
	SH-AR 08	−26.25	−62.25	Alberdi (Santiago del Estero)	13,507
	SH-AR 09	−26.75	−63.25	Figueroa (Santiago del Estero)	17,820
	SH-AR 10	−27.25	−62.25	Moreno (Santiago del Estero)	16,127
SA-US	SA-US 01	35.25	−105.25	San Miguel (New Mexico)	12,266
	SA-US 02	34.25	−103.75	Roosevelt (New Mexico)	6358
	SA-US 03	34.75	−104.75	Guadalupe (New Mexico)	7853
	SA-US 04	33.75	−104.75	De Baca (New Mexico)	6045
	SA-US 05	32.75	−101.25	Scurry (Texas)	5
	SA-US 06	32.25	−102.75	Andrews (Texas)	12
	SA-US 07	31.25	−101.75	Reagan (Texas)	3046
	SA-US 08	30.75	−101.75	Pecos (Texas)	19
	SA-US 09	29.25	−100.75	Val Verde (Texas)	8372
	SA-US 10	27.75	−99.75	Webb (Texas)	8744
SH-US	SH-US 01	37.25	−99.25	Comanche (Kansas)	2046
	SH-US 02	36.25	−99.75	Ellis (Oklahoma)	3191
	SH-US 03	35.75	−99.75	Beckham (Oklahoma)	2341
	SH-US 04	35.25	−101.25	Carson (Texas)	2393
	SH-US 05	34.25	−99.75	Hardeman (Texas)	1805
	SH-US 06	33.25	−99.25	Throckmorton (Texas)	4403
	SH-US 07	32.25	−99.25	Eastland (Texas)	7252
	SH-US 08	31.25	−99.25	McCulloch (Texas)	2779
	SH-US 09	30.25	−99.25	Gillespie (Texas)	2748
	SH-US 10	28.75	−98.75	Atascosa (Texas)	3201

use can respond to multiple factors (Lambin et al., 2001) other than climate variability (e.g., prices, profitability, policies, technology, etc.), we analysed the relationship between precipitation and land-use through residual analysis of both variables. To do this, we first defined the equations that describe the evolution of both variables over the complete period analysed (1901–2011) for each of the 40 sites. Secondly, based on these equations we calculated the trend values, obtaining a new time series for each variable and each site. Finally, the value of residues was obtained by estimating the difference between each recorded figure (original dataset) and the figure arising from the average temporal trend.

We assumed that the correlation resulting from simple regression analysis between the residuals of rainfall and the residuals of land-use can represent correctly the potential of land-use as an adaptative tool to face climatic variability across the last century. Therefore, a high correlation is indicative of a high sensitivity of land-use to climate variability. It means that farmers adapt to drought conditions through a reduction of the cultivated area or, on the contrary, by increasing the cultivated area when rainfalls allow it. When the sensitivity of land-use to rainfall variability declines, this would indicate that other variables (e.g., technology, agronomic practices) are allowing a more effective adaptation of farmers to climate disturbances.

However, farmers' decisions are normally influenced not only by the season-to-season or year-to-year rainfall variability, but also by the soil-water conditions that may extend from one farming period to the following (Viglizzo, 2011), as well as by economic factors referring to changes in short-term, such as grain prices or variable costs (Lambin et al., 2001). Because of that, we assumed that triennial averages could represent the predominant conditions that probably have influenced the farmers' decisions within each 3-year period and also smooth the short term influences.

Therefore, the historical residual time series for land-use and precipitation were grouped in triennial averages centred into the second year. The method consisted in calculating a new dataset for each variable and site using rolling windows. Thus, from the original residuals series with 111 data (a data for each year from 1901 to 2011), a new 37-dataset was obtained in which each one is the average of a triennial subset. By a sequential calculation of correlation coefficients through simple regression analysis between this new series of grouped residuals, we assessed changes in the land-use decisions to rainfall variability as the study proceeded in time.

2.4.3. *Assessing the importance of technology incorporation as adaptative strategy*

Assessing technology incorporation as an adaptative strategy in replacement of land-use decisions allowed us to quantify the evolution of the farmers' ability to maintain or increase the proportion of land allocated to annual crops despite the negative impacts of climate variability. The procedure that we followed to estimate the shift between adaptation strategies (land-use decisions vs. climate risk-mitigation technologies) consisted in linking the sensitivity of land-use decisions to climate variability, and later to the proxy for technology adoption through simple regression analysis. Thus, we tried to test if the relative importance of land-use change as an adaptative tool was successfully replaced by technological tools that have demonstrated to be effective to reduce the disturbing influence of climate.

3. Results and discussion

3.1. Historical characterization of studied areas

3.1.1. Climatic particularities

Semiarid and sub-humid environments in the Argentine Chaco have shown annual average temperatures exceeding 20 °C (Table 2, Fig. 2), classifying its climate as subtropical (Collado, 2000). Most sites analysed have had a mean temperature variation of 0.5 °C (Table 2) that was also observed in the long-term trends (Fig. 2). On the other hand, the US Southern Plains are classified within a subtropical-temperate climate (Trewartha, 1968) due that its average annual temperature has fluctuated between 11 and 23 °C (Table 2, Fig. 2). The inter-annual variability of the average temperature over the last century in the Southern Plains has been greater than that of the Argentine Chaco, amounting to 0.7 °C (Table 2). In addition, the mean temperature trends have also shown greater variability among sites (Fig. 2). In this case we can clearly see a natural temperature gradient across the study sites, associated with elevation. In general, the lowest average temperatures correspond to sites with higher altitude.

Precipitation in the regions of both countries has fluctuated between 300 and 700 mm per year over the last century with inter-annual variability that ranged between 90 and 150 mm (Table 2). However, some differences emerge when comparing the long-term trends. The greater extreme precipitation values between sites of the semiarid Chaco – in relation to the sub-humid environments – (Fig. 3) reflects its increased climate variability for grain cultivation. Despite long-term precipitation trends were smoothed by averaging rainfall data from 10 different sites, in Argentine Chaco can be appreciated the same behaviour across all sites: a more humid period (from 1960 to 2000) with average values close to or greater than 600 mm (Fig. 3).

Table 2
Averages and standard deviations of historical climatic characteristics and land-use pattern during the last century (1901–2011) for the study sites in the Argentine Chaco and US Southern Plains.

Agro-ecological area	Specific sites	Precipitation (mm/year)		Mean temperature (°C)		Potential et (mm/year)		Land use (% annual crops)	
		Mean	(+/– SD)	Mean	(+/– SD)	Mean	(+/– SD)	Mean	(+/– SD)
SA-AR	SA-AR 01	613.7	(+/– 142.1)	23.3	(+/– 0.7)	1493.3	(+/– 49.1)	0.046	(+/– 0.027)
	SA-AR 02	717.7	(+/– 154.0)	23.2	(+/– 0.6)	1468.1	(+/– 41.9)	0.052	(+/– 0.034)
	SA-AR 03	689.6	(+/– 126.4)	22.5	(+/– 0.6)	1435.4	(+/– 43.7)	8335	(+/– 5113)
	SA-AR 04	619.7	(+/– 120.2)	21.4	(+/– 0.5)	1406.5	(+/– 44.1)	2273	(+/– 1457)
	SA-AR 05	588.0	(+/– 128.9)	21.1	(+/– 0.5)	1433.1	(+/– 46.9)	1011	(+/– 0.842)
	SA-AR 06	550.0	(+/– 132.3)	19.0	(+/– 0.5)	1439.7	(+/– 46.5)	2560	(+/– 2112)
	SA-AR 07	466.2	(+/– 110.3)	19.8	(+/– 0.6)	1502.8	(+/– 46.8)	0.381	(+/– 0.427)
	SA-AR 08	392.1	(+/– 93.5)	20.2	(+/– 0.5)	1530.5	(+/– 45.1)	0.019	(+/– 0.018)
	SA-AR 09	372.6	(+/– 90.5)	20.9	(+/– 0.5)	1513.3	(+/– 42.5)	0.039	(+/– 0.019)
	SA-AR 10	335.3	(+/– 96.0)	19.9	(+/– 0.5)	1504.7	(+/– 42.5)	0.002	(+/– 0.001)
SH-AR	SH-AR 01	495.3	(+/– 94.5)	23.4	(+/– 0.7)	1577.3	(+/– 49.1)	0.033	(+/– 0.024)
	SH-AR 02	560.9	(+/– 99.9)	23.6	(+/– 0.7)	1613.7	(+/– 48.2)	0.008	(+/– 0.004)
	SH-AR 03	614.6	(+/– 112.0)	23.5	(+/– 0.7)	1607.6	(+/– 49.3)	0.018	(+/– 0.008)
	SH-AR 04	625.1	(+/– 134.0)	23.4	(+/– 0.6)	1585.8	(+/– 42.5)	0.014	(+/– 0.005)
	SH-AR 05	640.6	(+/– 128.0)	23.2	(+/– 0.6)	1610.2	(+/– 44.7)	0.063	(+/– 0.018)
	SH-AR 06	636.7	(+/– 126.3)	23.1	(+/– 0.5)	1591.8	(+/– 43.9)	0.021	(+/– 0.010)
	SH-AR 07	624.7	(+/– 118.7)	22.8	(+/– 0.5)	1567.4	(+/– 44.4)	0.163	(+/– 0.083)
	SH-AR 08	633.3	(+/– 122.5)	22.4	(+/– 0.5)	1582.0	(+/– 47.0)	0.742	(+/– 0.629)
	SH-AR 09	585.6	(+/– 115.4)	22.0	(+/– 0.5)	1518.4	(+/– 45.5)	0.117	(+/– 0.122)
	SH-AR 10	691.2	(+/– 142.9)	21.5	(+/– 0.5)	1575.5	(+/– 51.7)	5458	(+/– 4876)
SA-US	SA-US 01	376.0	(+/– 88.3)	11.1	(+/– 0.7)	1446.2	(+/– 59.1)	0.76	(+/– 0.21)
	SA-US 02	398.3	(+/– 109.7)	14.1	(+/– 0.7)	1613.5	(+/– 67.0)	10.2	(+/– 2.78)
	SA-US 03	333.6	(+/– 96.5)	13.0	(+/– 0.7)	1541.7	(+/– 59.9)	0.30	(+/– 0.08)
	SA-US 04	305.1	(+/– 91.4)	14.7	(+/– 0.7)	1628.4	(+/– 67.8)	0.65	(+/– 0.18)
	SA-US 05	451.0	(+/– 134.1)	17.5	(+/– 0.7)	1769.5	(+/– 96.9)	16.6	(+/– 3.11)
	SA-US 06	351.4	(+/– 119.5)	17.4	(+/– 0.7)	1811.0	(+/– 80.1)	6.90	(+/– 1.40)
	SA-US 07	388.0	(+/– 123.5)	18.3	(+/– 0.7)	1765.6	(+/– 86.4)	2.05	(+/– 0.38)
	SA-US 08	385.6	(+/– 121.5)	18.8	(+/– 0.7)	1759.9	(+/– 84.8)	0.40	(+/– 0.07)
	SA-US 09	468.0	(+/– 145.4)	21.6	(+/– 0.7)	1683.1	(+/– 91.6)	3.84	(+/– 0.60)
	SA-US 10	442.4	(+/– 130.6)	23.1	(+/– 0.7)	1784.5	(+/– 95.0)	3.89	(+/– 1.15)
SH-US	SH-US 01	613.3	(+/– 142.2)	14.4	(+/– 0.7)	1546.6	(+/– 90.5)	36.74	(+/– 3.78)
	SH-US 02	568.5	(+/– 123.7)	15.1	(+/– 0.7)	1641.3	(+/– 86.4)	24.95	(+/– 3.87)
	SH-US 03	626.7	(+/– 140.0)	15.6	(+/– 0.7)	1674.4	(+/– 91.6)	22.19	(+/– 3.60)
	SH-US 04	534.2	(+/– 122.0)	14.4	(+/– 0.6)	1650.1	(+/– 83.6)	36.67	(+/– 6.81)
	SH-US 05	603.9	(+/– 170.9)	16.7	(+/– 0.7)	1674.1	(+/– 97.1)	32.20	(+/– 5.48)
	SH-US 06	677.2	(+/– 158.4)	17.9	(+/– 0.7)	1665.0	(+/– 90.6)	16.21	(+/– 3.01)
	SH-US 07	692.3	(+/– 171.2)	18.2	(+/– 0.7)	1631.5	(+/– 91.4)	16.80	(+/– 3.14)
	SH-US 08	635.9	(+/– 157.3)	18.5	(+/– 0.7)	1560.8	(+/– 85.6)	19.45	(+/– 3.64)
	SH-US 09	645.1	(+/– 184.9)	18.7	(+/– 0.7)	1491.2	(+/– 86.9)	8.13	(+/– 1.52)
	SH-US 10	616.2	(+/– 161.3)	21.8	(+/– 0.7)	1602.8	(+/– 85.5)	18.20	(+/– 3.40)

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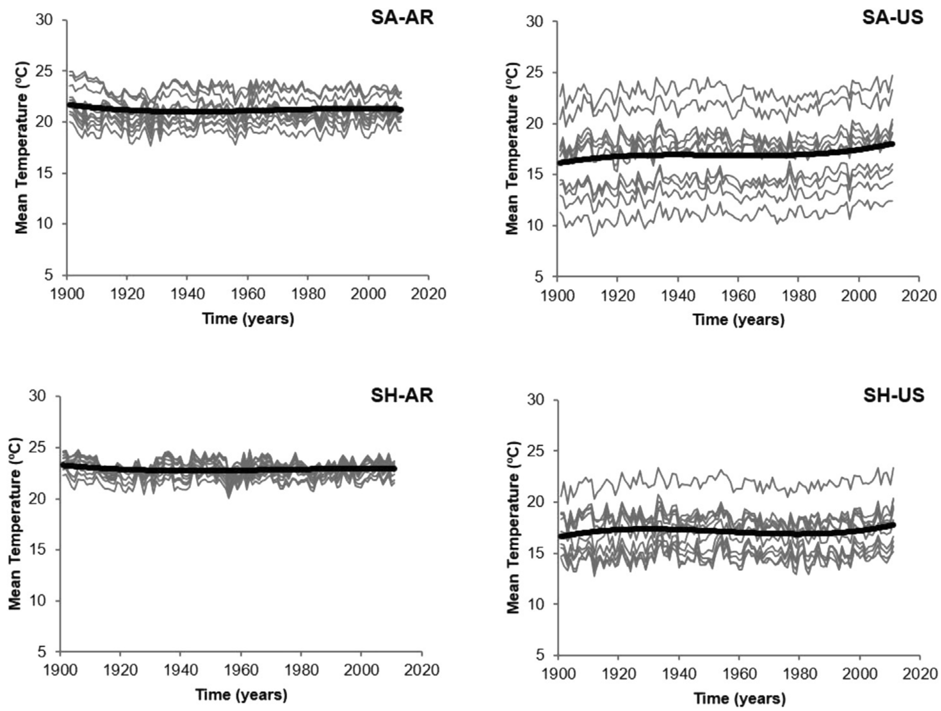

Fig. 2. Mean temperature of 40 geographical sites in the semiarid and sub-humid environments of the Argentine Chaco and the US Southern Plains between 1901 and 2011. References: (SA-AR) Semiarid Argentina; (SH-AR) Sub-humid Argentina; (SA-US) Semiarid United States; (SH-US) Sub-humid United States. Continuous grey lines represent the variability in the values of each site and black line represents the average values of all evaluated sites.

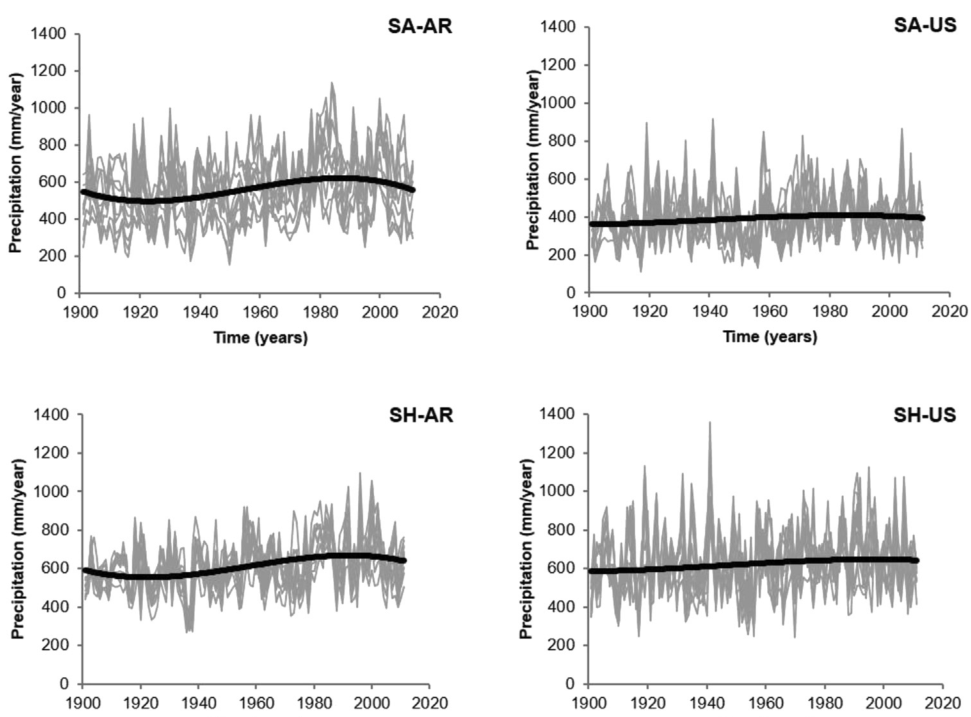

Fig. 3. Precipitation of 40 geographical sites in the semiarid and sub-humid environments of the Argentine Chaco and the US Southern Plains between 1901 and 2011. References: (SA-AR) Semiarid Argentina; (SH-AR) Sub-humid Argentina; (SA-US) Semiarid United States; (SH-US) Sub-humid United States. Continuous grey lines represent the variability in the values of each site and black line represents the average values of all evaluated sites.

In the US Southern Plains, the difference between the total rainfall between sub-humid and semiarid environments has been much more marked (Table 2), detecting a significant gradient between the highest average annual rainfall in the East that decrease progressively to the West. The inter-annual variability has been greater in the sub-humid zone with variations up to 185 mm from one year to another (Table 2). In the historic rainfall trends of this region, there has not been a wet period as marked as in northern Argentina (Fig. 3). Although the precipitation has usually been suitable for agriculture, it has an increasingly prominent summer concentration, due that roughly a third to half of the total falls during October to March in Argentine Chaco and April to September with June maximum in the US Southern Plains (Chen et al., 1996; Gorleri, 2005).

Throughout the last century, in both regions compared, high potential evapotranspiration (PET) rates have far exceeded precipitation (Table 2, Fig. 4), producing a negative water balance (Gorleri, 2005). PET has varied between 1400 and 1800 mm per year, observing the highest rates in the semiarid zone of US (Table 2, Fig. 4). In addition, this area also has had the largest difference of historical trends between sites. Generally, in the Argentine Chaco, annual PET has varied around 50 mm, while in the US Southern Plains this value was doubled (Table 2, Fig. 4).

3.1.2. Agriculture development

Regarding land-use, the Chaco and the Southern Plains have had some features in common but have differed in some other aspects. In both regions land-use have fluctuated over time, producing markedly different historical patterns of agricultural use (Fig. 5). At the beginning, most of the changes in cropland uses occurred due to transitions between cropland uses and pasture/rangeland (Nickerson et al., 2011). Although currently, crops are grown on a vastly increased scale of production, early last century, the percentage of area planted with annual crops was low (Baldi and Jobbágy, 2012).

In the Argentine Chaco, the development of agriculture has initiated in the early decades of the 20th century. Since then, land has been developed to grow crops, at the expense of natural forest cover (Sili et al., 2011). In this region, agriculture has occurred and expanded under a high diverse array of social condition, leading to contrasting land-uses (Baldi et al., 2014). In general, cultivation levels have remained fairly low and a weak tendency to increase cropped area was only apparent from the 1990's (Table 2; Fig. 5). Anyway, croplands in the Chaco continued expanding until today with a strong move towards the West, due to climate marked positive deviations, as well as the incorporation of new techniques, particularly direct seeding (Torrella et al., 2005). This is clearly linked to the advance of oilseeds and cereals (Reca, 2006; Sili et al., 2011).

On the other hand, since 1900, farmers in the US Southern Plains have cultivated under a larger, more mechanized, less labour intensive and more specialized cropping scheme (Walthall et al., 2012). The percentage of cultivated area has steadily expanded (Fig. 5), especially in sub-humid environments that have showed about twice the proportion of cropped land than semiarid environments (Table 2) Today, the Southern Plains, although a large proportion of land is allocated to livestock production under extensive grazing schemes (Nickerson et al., 2011; Sili et al., 2011), holds croplands shares above the national average (Nickerson et al., 2011).

Many factors can explain the huge difference in the rate of cropland increase in both countries, but it is likely that the need for farmers to address climate fluctuations had a big influence. This mismatch between the studied regions may be due the early adoption of hybrid seeds (Reca, 2006) and the contribution of conservation-tillage methods also initiated several decades ago (Peterson, 2005) in the US Southern Plains. On the other hand, annual crop cultivation in the Argentine Chaco has developed under rain-fed conditions with no input of irrigation water (Baldi and Jobbágy, 2012; Baldi et al., 2013), while the vast cropping region of the US Southern Plains has shown a trend towards increased irrigation that started in 1940's (USDA, 2008; USGS, 2013). For 2007, this region accounted about 15 percent of total US irrigated area (Schaible and Aillery, 2012). Maize has the

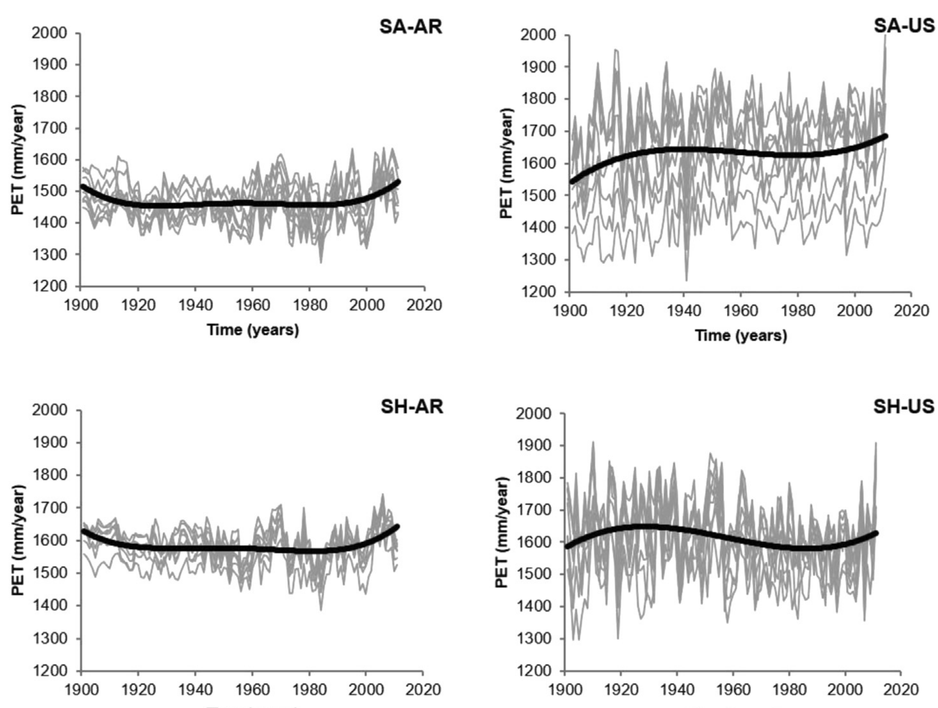

Fig. 4. Potential evapotranspiration (PET) of 40 geographical sites in the semiarid and sub-humid environments of the Argentine Chaco and the US Southern Plains between 1901 and 2011. References: (SA-AR) Semiarid Argentina; (SH-AR) Sub-humid Argentina; (SA-US) Semiarid United States; (SH-US) Sub-humid United States. Continuous grey lines represent the variability in the values of each site and black line represents the average values of all evaluated sites.

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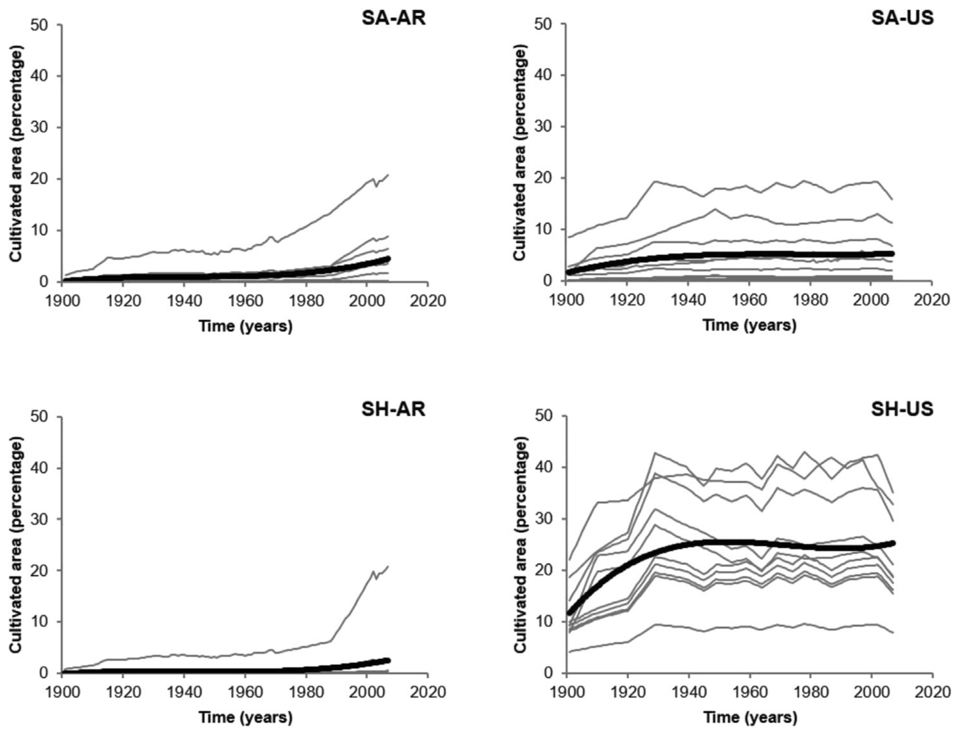

Fig. 5. Cultivated area (relative values) in the study geographical sites of the semiarid and sub-humid lands of Argentine Chaco and the US Southern Plains between 1900 and 2007. References: (SA-AR) Semiarid Argentina; (SH-AR) Sub-humid Argentina; (SA-US) Semiarid United States; (SH-US) Sub-humid United States. Continuous grey lines represent the variability in the values of each site and black line represents the average values of all evaluated sites.

greatest reported irrigation levels, accounting for about 25 percent of all harvested irrigated crops, since it is known to be sensitive to water deficits (USDA, 2008; Schaible and Aillery, 2012).

3.2. Temporal behaviour of the components of variance

As mentioned above (Section 2.4.1), datasets were initially subjected to a PCA to reduce dimensionality. Table 3 shows the proportion of total variance explained by the first two components, and how this proportion varies across the three periods and four environments considered. The results show a substantially different behaviour between the Chaco and US sites. While the total variance and the percentage of variance accounted by the first two principal components (PC1 and PC2) showed a clear long-term decline in the two Chaco environments, the corresponding patterns in the US environments were much less distinct. The highest percentage of the variance of the PC1 was loaded on the Argentine Chaco. The comparison of those behavioural patterns suggested that the most promising adaptative reaction to the climatic disturbance could be expected in the semiarid and sub-humid environments of Argentina. To get a more thorough interpretation of changes in the variance, it was necessary to discriminate among the climatic and land-use analysed factors.

The behaviour of discriminated factors is shown in Fig. 6. Climatic factors (mean, maximum and minimum temperature, precipitation, and potential evapotranspiration) on the one hand, and land-use (% annual crops) on the other hand, were displayed across *X* and *Y* axis (PC1 and PC2, respectively) during the 1901–1930, 1931–1960 and 1961–2007 periods. The most significant changes of variance are detected in SA-AR and SH-AR for precipitation and land-use when the analysis moved from one period to the following. It is interesting that while the variance for rainfall tended to increase, the variance for land-use tended to decline throughout the century. A similar behaviour was not detected in US. The contrasting behaviour of the variance suggests that the adaptative

Table 3
Component weights of study sites in the Argentine Chaco and US Southern Plains across the three periods.

Agro-ecological area	Period	Component number	Percent of variance	Cumulative percentage
SA-AR	1901	1	68.793	68.793
	−1930	2	16.999	85.791
	1931	1	60.705	60.705
	−1960	2	20.977	81.682
	1961	1	56.693	56.693
	−2007	2	23.122	79.815
SH-AR	1901	1	76.347	76.347
	−1930	2	16.628	92.974
	1931	1	69.844	69.844
	−1960	2	14.477	84.321
	1961	1	53.444	53.444
	−2007	2	24.289	77.733
SA-US	1901	1	59.791	59.791
	−1930	2	19.158	78.950
	1931	1	60.555	60.555
	−1960	2	24.160	84.715
	1961	1	56.101	56.101
	−2007	2	22.635	78.736
SH-US	1901	1	59.336	59.336
	−1930	2	22.465	81.801
	1931	1	65.295	65.295
	−1960	2	21.817	87.112
	1961	1	57.153	57.153
	−2007	2	22.752	79.905

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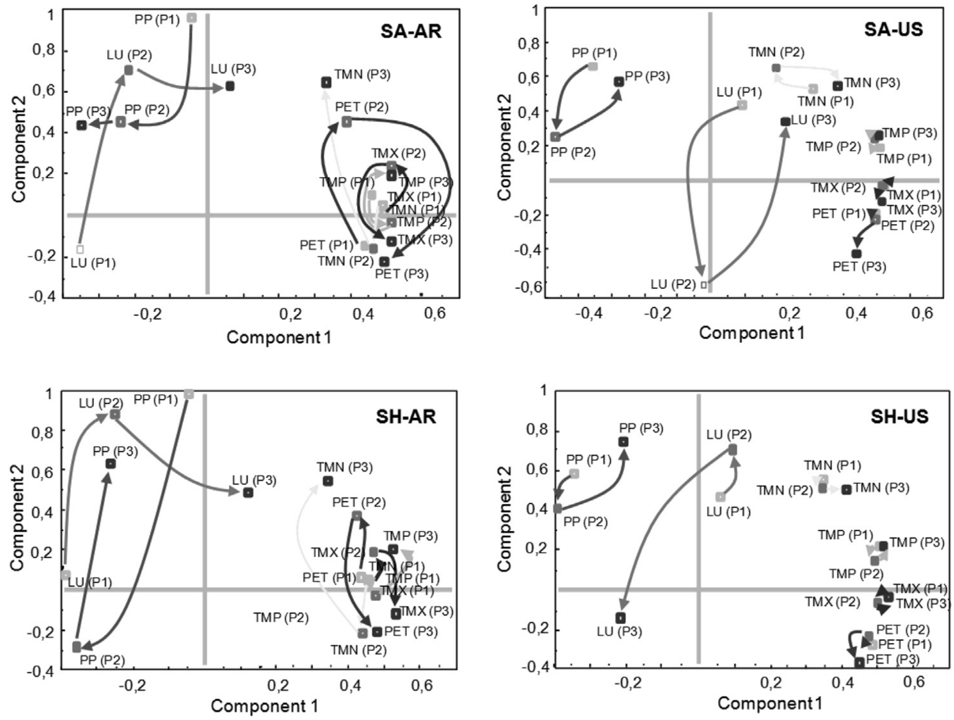

Fig. 6. Components of variance across time in semiarid and sub-humid areas of the Argentine Chaco and the US Southern Plains. References: (PP) Precipitation; (PET) Potential evapotranspiration; (TMN) Minimum temperature; (TMP) Mean temperature; (TMX) Maximum temperature; (LU) Land use; (P1) Period between 1901 and 1930; (P2) Period between 1931 and 1960; (P3) Period between 1961 and 2011.

mechanisms to climate variability were basically different in Argentina and US. These results insinuate the hypothesis that other factors not visible in the data, such as technology, could explain the process. The variance of temperature and potential evapotranspiration did not show significant changes in any of the four analysed regions. Then, the analytical focus was put on the relationship between precipitation and land-use, which clearly shows a reverse trend in the Argentine Chaco.

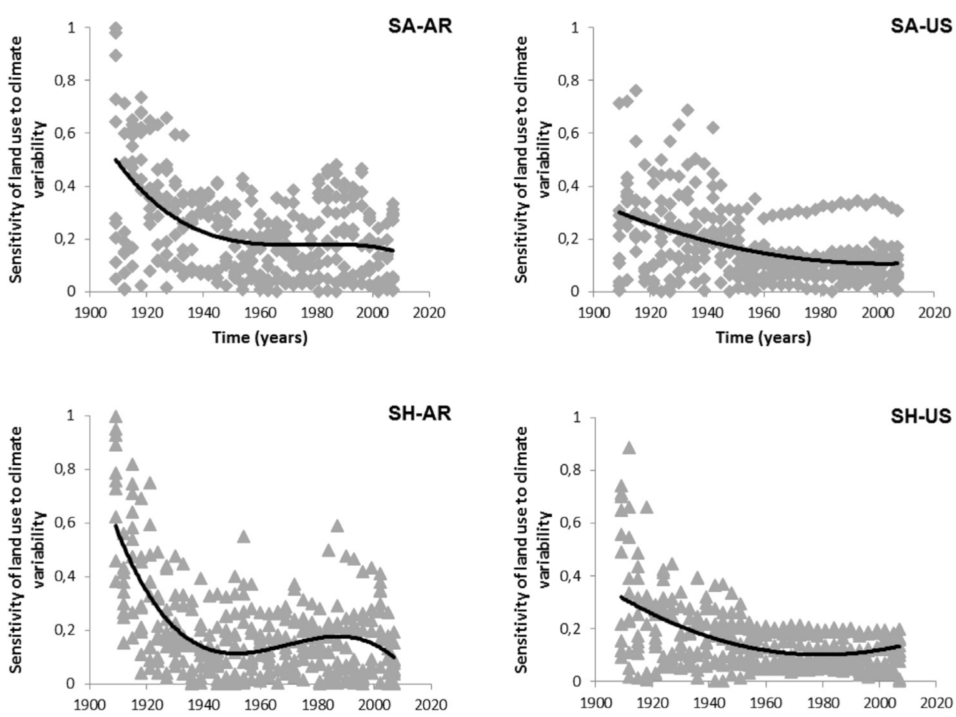

Fig. 7. Sensitivity of cultivated land to climate variability of 40 sites between 1901 and 2007 in the Argentine Chaco and US Southern Plains. References: black line represents the average temporal correlation.

3.3. Land-use change and technology adoption as indicators of farmers to face climate related risks

As mentioned above (Section 2.4.2), we assumed that the correlation arising from simple regression analysis between the residuals from trends in rainfall and land-use, shows how farmers have used cultivation, through land-use decisions or technology, as an adaptative tool to minimize the impact of climatic disturbances throughout the last century. Fig. 7 shows for each rural environment, the correlation trends of the 10 sites that comprise them for each year. Then, if we accept that assumption and only analyse the average temporal correlation, is possible to see predominant high correlation coefficients during the first half of the 20th century showing the sensitivity or ability of farmers, both in Argentina and US, to link their decisions (planting or not planting) to the variability of their local climate. Nevertheless, such sensitivity seemed to decrease after the 1940s in the US and the 1960's in Argentina (Fig. 7). This suggests that strategies other than land-use were employed for climate adaptation. The lower sensitivity shown by farmers in the US Southern Plains during the second half of the 20th century and the early 21st century allows us to infer that the adaptative potential of the US farming sector has been greater than that of Argentina. If we link this evidence to the results of Fig. 6, it appears that farmers in southern US have incorporated more effective technological tools than farmers in Argentina to neutralize the impact of rainfall variability.

The analysis of the dominant technological features and their adoption rates throughout the century seemed to be necessary to assess the adaptation process in both regions. Different indicators can be used as proxies for technology adoption like the change in irrigated areas, fertilizers and pesticides applied, the use of improved genotypes, or the use of conservation-tilling practices. However, Antle (2009) demonstrated that, as a result of different simulation models, increases in crop yield reflected the application of a full technology package.

Results from Calviño et al. (2003) in Argentina show that maize yield increases were related to technology adoption in different stages during the recent decades: i) from the late 1980s to the mid-1990s, mainly explained by P fertilization, better and earlier weed control, and improved hybrids; ii) from the mid-1990s to 1996–1998, related to no-till and higher plant density; and iii) from 1996–1998 to 1999–2000, mainly explained by enhanced rates of N fertilization. On the other hand, maize yield in US changed very little from 1866 to 1930, an era of low-input agriculture, but it increased rapidly from 1950 to the present as the low-input system gave way to a high-input system that utilized commercial hybrids, manufactured N fertilizer, herbicides, and higher plant populations (Egli, 2008).

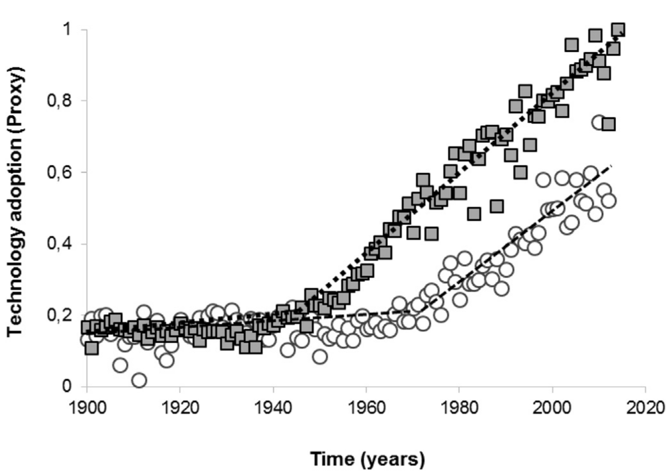

Fig. 8. Proxy for technology adoption between 1901 and 2011 in the Argentine Chaco and US Southern Plains. References: white circles correspond to Argentine Chaco, whereas grey squares show values for the US Southern Plains. Dotted lines indicate where the main trend change takes place: 1940 for US and 1970 for Argentina.

That combined innovations have positively impacted on maize yield, improving the use of water and attenuating the inter-annual oscillations of rainfall in water-constrained areas (Tilman et al., 2002). For that reason, we utilized historical statistical data of maize yield as a proxy that accurately represents the response of that crop to the application of multiple technological practices. Despite the inter-annual variability, the long-term yield increase in semiarid and sub-humid areas is a reliable indicator of the adaptative capacity of that crop to absorb the negative impact of climate.

Ranging from 0 to 1, the estimated proxy for technology incorporation is presented for both regions with their respective adoption rates by the rural sector (Fig. 8). The dotted lines describing the trajectory of the general trend of the proxy, show that until 1930, the adoption of technology in Argentina and US were similar.

Due to the early adoption of hybrid seeds in US associated with the production of semi-hard maize (Reca, 2006), a gap was detected after the 1940 decade. During the II World War, US had the need of supplying food to its allies, then stimulating the adoption of technologies, some of which were available but still unused (Reca, 2006). In the case of maize, there was an extensive use of fertilizers and herbicides, which reinforced the effect of hybrid adoption and price-support policies (Reca, 2006).

In Argentina, historically specialized in the production of hard maize (flint), the acceptance of new hybrids occurred two decades later in response to market forces (Reca, 2006). Was at the beginning of the 1960s when the growing impact on yield of improved seeds begins to be felt, increasing its intensity during the seventies and early eighties (Gutiérrez, 1988).

Generally, throughout the last century, the study areas in both countries show a reduction in the sensitivity of cultivated land to climate variability that can be attributed to the adoption of technology as an adaptative strategy. However, the adoption of technology has had a climate-adaptative impact in the US Southern Plains since the 1940's, while the same process occurred in the Argentine Chaco 30 years later.

The important issue of strategies replacement is presented in Fig. 9. Our methodological assumption that the relative importance of land-use as adaptative strategy declined at the same time that the value of the technology adoption increased seems to be confirmed. Then we can infer that a successful substitution of adaptative strategies has occurred in favour of the technological innovation. The process of substitution of land-use in response to technological change seems to have been previous in the US Southern Plains and more evident and potent in the Argentine Chaco.

Hypothetically, the different trajectories of technological models in both regions can be explained by the fact that the US agriculture was the first to begin a trajectory, the modern one, articulated to the "Productivist Paradigm" resulting from the Green Revolution (Borlaug and Doswell, 2000) which has a strong moderating effect on climate variability. It was based on the use of high yield varieties with higher drought resistant which achieved very superior crops to those of indigenous seeds by being irrigated and fertilized (Borlaug and Doswell, 2000). Some authors (McDonald and Girvetz, 2013) found that for past drought events, US farmers, somewhat logically, installed more irrigation equipment and put more water down on fields that were already irrigated. Beyond these response of the use of irrigation by US farmers to face climate variability, the authors also note a historical trend toward greater irrigation

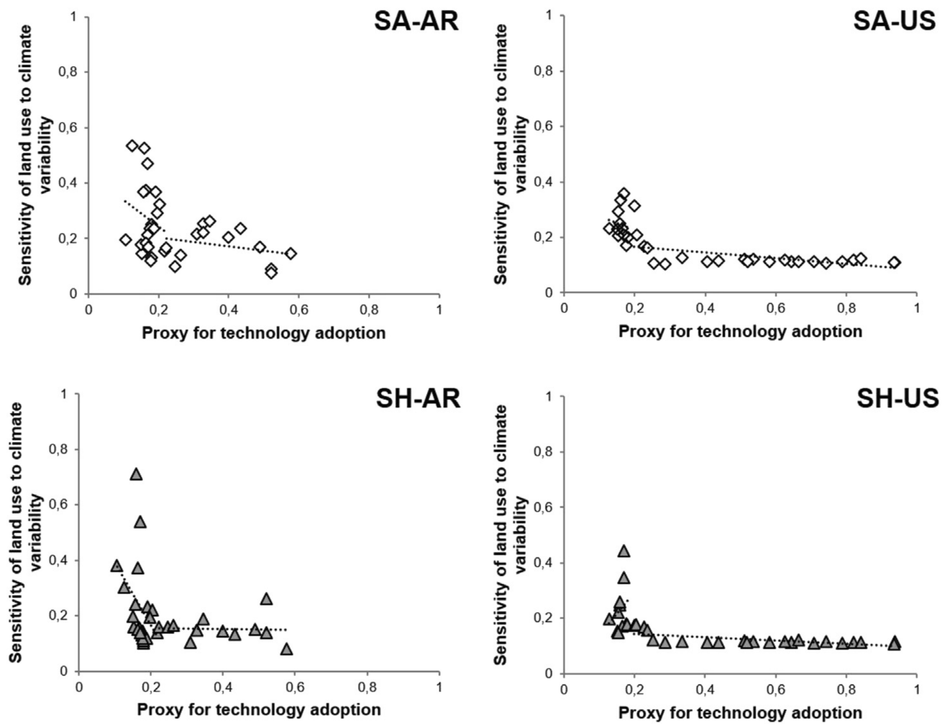

Fig. 9. Sensitivity of cultivated land to climate variability of study sites in response to technology adoption between 1901 and 2007 in the Argentine Chaco and the US Southern Plains.

efficiency. Nevertheless, a greater fertility of ground and availability of humidity improved the ecology of weeds, plagues and diseases, thus making it necessary to introduce chemical products to combat them (Borlaug and Doswell, 2000). It model prevailed during the second half of the last century in the irrigated agriculture which occupies a fifth part of the total of harvested hectares in US (USDA, 2008). All this, was accompanied by conservation-tillage methods initiated several decades ago in US (Peterson, 2005) and a more recent adoption of yield monitoring and VRA (Variable Rate Application) fertilization (Swinton and Lowenberg-DeBoer, 2001).

On the other hand, the Argentine Chaco has remained handling a traditional rural trajectory for a longer period of time. Has prevailed a cropping scheme under rain-fed conditions (Baldi and Jobbágy, 2012; Baldi et al., 2013) where the use of site-specific fertilization is rare, and generally, lies on the efficient frontier line in their labour and tractor use (Swinton and Lowenberg-DeBoer, 2001). Irrigation was never incorporated extensively into the Argentine agriculture, having occasional problems in water supply for agriculture and higher vulnerability to rainfall extremes and drought (Rosenzweig et al., 2004) and making it dependent to climate (Baldi et al., 2014). In this region, agricultural lands currently hold a diverse spectrum of farming offering variable management conditions (Baldi et al., 2014). Different farming strategies, such as the implementation of flexible and cropping sequences depending on water availability, could help to deal with climate and yield variability (Giménez et al., 2014). Despite this, the impact of technology replacement under rain-fed conditions in North Argentina has had an abrupt and noticeable effect both, in semiarid and sub-humid lands.

4. Conclusions

The results from this research demonstrate that, although in dissimilar ways and at different times, two stages of adaptative strategies to climate variability have taken place during the last century in the studied regions of Argentina and US. In both countries, during the first stage, adaptation was strongly driven by changes in land-use strategies. The high sensitivity of the cultivated area during the first third of the 20th century in the Southern Plains, and during the first half of that century in Chaco, demonstrated that farmers have adapted to the climate disturbance through the simple binary decision of planting or not planting. During the second stage, on the other hand, the adaptative process seemed to have been driven by technology adoption, although this stage appeared to have started three decades later in Chaco than in the Southern Plains.

The adoption of technologies and agronomic practices would explain the sensitivity decay of the cultivated area to the climatic variability. The incorporation of improved hybrids, drought-resistant varieties, the adoption of minimum tillage and no-till practices, and the implementation of irrigation practices were the core of this adaptative process primarily in US.

The sensitivity of agricultural to climate variability depends on future technological progress and crop adaptation, among many other factors. More integrated efforts are needed to develop knowledge taking into account environmental effects on farmer's behaviour. Most measures to increase past adaptation also have a high potential to maintain or increase adaptation levels under future climatic conditions, e.g., with enhanced water management. Whether such adaptation can be realized will largely depend on socio-economic factors of each region.

It should be noted that the more important methodological difficulty in this research arose when we had to quantify the technology-adoption process. The diversity of available technologies and practices, and the lack of quantitative data showing adoption rates, led us to evaluate the adoption process by means of the increasing maize yield as a result of the application of multiple technologies. Although this proxy based procedure can be

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questioned, it allowed us to get a first explanatory approach about the potential of technology as an adaptative factor to face the worrying signals of climate variability.

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