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Precipitation event distribution in Central Argentina: spatial and temporal patterns

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ABSTRACT

The annual amount of precipitation inputs received by a site during a full year is considered a dominant spatial and temporal control of primary productivity and other related process in arid to subhumid ecosystems. However, to be effectively used by plants, these inputs have to escape runoff, favoured by large and less frequent precipitation events, and evaporation losses, favoured by small and more frequent events. Thus, available water for plant transpiration is not only influenced by the annual sum of precipitation events but also by their frequency-size distribution. In this paper, we characterize this distribution and its association to total annual precipitation inputs through space (five sites along a tenfold precipitation gradient across 1000 km) and time (1961–2010) in the plains of central Argentina. We decomposed total precipitation into two structural components, which are the frequency and mean size of events, showing that they have similar contributions (log–log slopes ≈ 0·5) explaining precipitation shifts in space. Over time, however, we found a preponderance of mean event size explaining precipitation fluctuations, particularly towards wetter sites (log–log slopes increasing from 0·61 to 0·88). The relative variability of event sizes, independent of their mean size (i.e. inequality), was numerically characterized with Gini coefficients derived from Lorenz curves, which showed highly constant values in space and time. Assuming fixed event-size thresholds for evaporation and runoff, and ignoring other controls beyond precipitation structure, the proportion of water potentially available for plant transpiration grew with total precipitation, raising from 0·45 to 0·71 from the driest to the wettest sites, but displaying stronger responses to total precipitation in time, particularly in drier sites. No long-term trends in any of the precipitation structure variables were detected. Response functions of frequency and mean size of events to annual precipitation together with Lorenz curves appeared to be robust descriptors of precipitation regimes that, not requiring any a priori assumptions, are useful to assess how spatial and temporal shifts in total precipitation may concurrently affect its relative availability for plant transpiration. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS Lorenz curves; precipitation structure; rainfall gradients; water balance; climate change

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INTRODUCTION

The amount of precipitation inputs received by terrestrial ecosystems is a key driver of their functioning (Weltzin *et al*., 2003; Yaseef *et al*., 2010). In arid, semi-arid and subhumid ecosystems, higher precipitation inputs and lower losses by evaporation, runoff and deep drainage translate into greater plant transpiration and primary productivity (Noy-Meier, 1973; Huxman *et al*., 2004a; Loik *et al*., 2004; Newman *et al*., 2006). In these systems, water losses by deep drainage typically represent a small fraction of the water balance (Scanlon *et al*., 2005; Contreras *et al*., 2012; Marchesini *et al*., 2013), whereas evaporation and runoff compete more strongly with transpiration. Even though the analysis of the role of precipitation in controlling ecosystem functioning often focuses on its annual amount, many studies have highlighted how the temporal distribution of precipitation inputs among years, seasons within a year, and frequency (i.e. number) and size of individual events can strongly affect the partition between water losses (Knapp *et al*., 2002; Schwinning and Sala, 2004; Heisler-White *et al*., 2009; Liu *et al*., 2012; Turnbull *et al*., 2013). In this study, we explore the distribution of precipitation events and its role driving water availability for plant transpiration in central Argentina, characterizing the variability of the frequency and size of precipitation events and its association with total precipitation inputs across time and space.

The structure of precipitation inputs, defined as the distribution of events according to their frequency and size for a given period and a given location, influence the proportion of these inputs that becomes available to plants. Precipitation occurs as temporally and spatially

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discrete pulses, and the frequency and the size of these pulses determine their penetration depth and duration into the soil (Breshears and Barnes, 1999; Schwinning and Sala, 2004). With similar total inputs, an extreme distribution characterized by very frequent but small pulses would maximize evaporation losses, whereas on the other end, one of infrequent but large pulses would maximize runoff (Bates *et al*., 2006). A number of experiments reported during the last decade for semi-arid systems have manipulated the frequency and size of events, maintaining the same annual precipitation inputs, revealing that, in general, less but larger events increased soil water availability and primary production (Knapp *et al*., 2002; Harper *et al*., 2005; Huxman *et al*., 2005; Bates *et al*., 2006; Yahdjian and Sala, 2006; Liu *et al*., 2012; Hao *et al*., 2013).

The role of event frequency-size distribution in the partition of the water fluxes into water available to plants and water lost motivated the exploration of general patterns in the structure of precipitation inputs and the development of mathematical approaches to describe them. The two broadest paths have been an analytical and a numerical one. The application of analytical approaches (Sethna *et al*., 2001), which describe the structure of precipitation on the basis of a small and universal set of parameters, allows for the comparison of locations or periods using common and simple metrics for the whole event distribution. More commonly used to assess precipitation regimes and their shifts in time and space, these first types of approaches are less frequently used to display ecologically meaningful patterns, perhaps because ecologist would rather deal with actual data than assuming specific event-distribution functions (Davidowitz, 2002). Particularly insightful among these analytical approaches, however, has been the application of power laws describing the inverse relationship between the frequency of events and their size (Sethna *et al*., 2001), both across time (single events, months, years) (Peters *et al*., 2002) and climatic gradients (e.g. sites ranging 300–3000 mm year^{-1}) (Sadras, 2003). The second type of approach, directly oriented to cast light on ecological and hydrological questions rather than to explore universal climatic patterns, has been numerical and considered empirical precipitation thresholds to filter climatic variability (Sala and Lauenroth, 1982; Reynolds *et al*., 2004). These numerical analyses, in spite of their limitations, considering the effects of vegetation heterogeneity or soil properties, were conceived to explore the partition of ecologically relevant water fluxes based on fixed thresholds that were considered appropriate for each study system (Sala *et al*., 1992; Golluscio *et al*., 1998; Lauenroth and Bradford, 2009).

The plains of central Argentina span 1000 km from the eastern foot slope of the Andes to the Atlantic coast, along which mean precipitation increases from ~100 to ~1000 mm year^{-1}. During the 20th century, the entire region experienced a dry period (1930–1960) followed by a wet one (1960–2000) (Minetti *et al*., 2003; García and Pedraza, 2008). These climatic shifts, which had been linked to long-term atmosphere/ocean circulation oscillations (Agosta and Compagnucci, 2012), and also to climate warming (Villalba *et al*., 1998; Labraga and Villalba, 2009), were accompanied by a contraction of the cultivated area during the first half of the century and a very strong expansion during the second half (Aizen *et al*., 2009), favoured, in this last period, by technological changes and high international grain prices (Viglizzo *et al*., 1997). Because of the key role that the onset of no-till agriculture had on this expansion process, simultaneously reducing evaporation and runoff water losses, understanding to what extent each one of this pathways is favoured by event frequency-size distribution shifts with increasing aridity becomes important (Viglizzo *et al*., 2001; Caviglia *et al*., 2004). Currently, there is a well-defined boundary for rainfed agriculture at a mean precipitation value of 700 mm year^{-1}, to the west of which natural vegetation becomes the most common land cover (Viglizzo *et al*., 2001; Baldi and Paruelo, 2008). Understanding how the distribution of precipitation events varies with total precipitation inputs in space and time, and to what extent it shows long-term shifts in response to long-term ocean circulation or global warming trends, will help to understand how future shifts in precipitation regimes may condition the availability of water for plants.

In this paper, we use a novel approach to characterize the distribution of precipitation events in response to total precipitation amounts focusing on the spatial (1000 km long) and temporal (1960–2010) gradient of the plains of central Argentina. For this purpose, we decomposed the total precipitation inputs for any given year and location (our study unit) into the number of events (frequency) and their mean size, exploring relative size distributions with Lorenz curves (Weiner and Solbrig, 1984). To explore how the distribution of precipitation events may shape water availability for plants across total precipitation gradients in space and time, we applied fixed evaporation and runoff thresholds to the annual precipitation records.

METHODS

We focused our study in the plains of central Argentina (−30°; −36° latitude, −70°; −60° longitude), along a precipitation gradient of 100–1000 mm year^{-1}, across the ecological regions of Monte, Chaco, Espinal and Pampa (Figure 1A) (Carreño *et al*., 2012). Datasets of 50 years of daily precipitation (1961–2010), obtained from the National Weather Service of Argentina, were used. The climate of the region is arid/semi-arid on the west, with average annual temperatures of 13 ºC and a wide seasonal

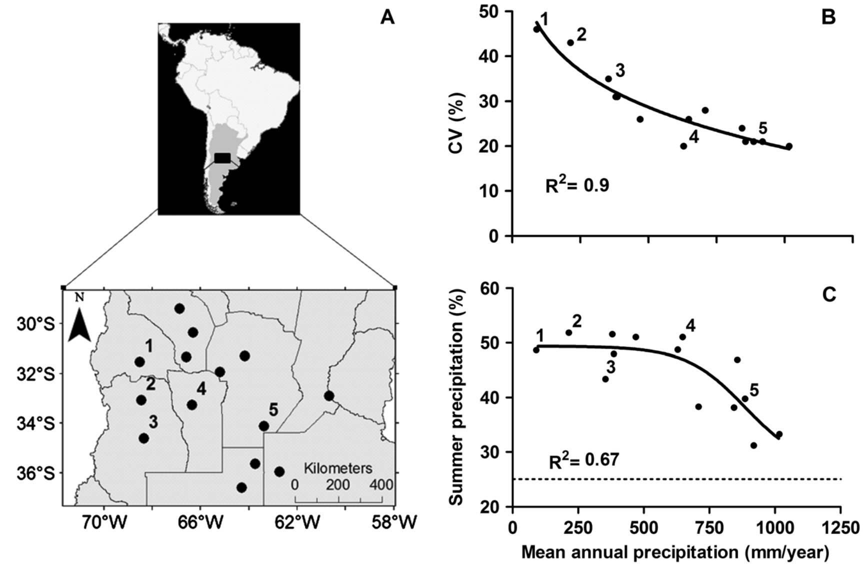

Figure 1. (A) Study region in central Argentina. Each marker represents the location of the weather stations plotted in B and C. Numbers 1–5 correspond to San Juan, San Martin, San Rafael, San Luis and Laboulaye, respectively, the sites analysed in detail by this paper. (B and C) Coefficient of variation (B) and proportion of summer precipitation (December–January–February) (C), as a function of mean annual precipitation. The dotted line shows the expected contribution (25%) under non-seasonal conditions.

temperature range, and semiarid/subhumid on the east, with average annual temperatures of 15 °C and a narrower seasonal temperature range. The region has higher inter-annual and seasonal variability of precipitation towards the arid end of the gradient (Figure 1B and C). Convective precipitations with high incidence of hail prevail towards the west, whereas frontal precipitations become increasingly important towards the east, where the influence of the Atlantic Ocean is stronger (Vera *et al*., 2006; INTA, 2010). We chose five precipitation series representing this gradient, located in San Juan, San Martín, San Rafael, San Luis and Laboulaye (sites 1, 2, 3, 4 and 5, respectively) (Figure 1).

The analysis of precipitation event distribution was based on daily data and considered an event to be any day with precipitation ≥0·1 mm. Any group of consecutive days with precipitation ≥0·1 mm was considered to be a single event (Reynolds *et al*., 2004). The minimum unit of analysis was each calendar year at each site (in total 250 year/sites). For each year/site, we first decomposed total precipitation into two components: frequency of events (i.e. number of events taking place during the whole year) and mean size of events (i.e. average size of events during the whole year). Then, for a given year,

$$\text{Total precipitation} = \text{frequency of events} * \text{mean size of events}$$

The relative weight of each component in the equation explaining total precipitation shifts was evaluated with log–log regressions. The slopes with which the logarithm of the components (frequency and mean size) scales with the logarithm of their product (total precipitation) are complementary and add one. An equal weight of these two components involves slopes of 0·5, and any deviation from this value illustrates the dominance of one component over the other determining total precipitation shifts. We used the theoretical slope value of 0·5 as a null hypothesis (i.e. balanced contribution of components) against which the observed slopes were evaluated (*t*-test). We constructed three groups of log–log models. The first was a general 'spatial-temporal' model based on the individual 250 years/site values. The second was a single 'spatial' model based on 50-year averages of total precipitation, frequency of events and mean size of events for the five study sites. Finally, we obtained five 'temporal' models developed for each individual site based on year to year variability. We compared the 'temporal' models with the 'spatial' one in order to explore to what extent precipitation series from one site could be extrapolated to another site with a different mean precipitation in order to represent wetter or drier conditions in simulation models or other types of studies. For this purpose, we used a multiple regression model pooling the spatial and temporal datasets and differentiating them with a dummy variable. The significance of the slope of this dummy variable in the model provides an integrative evaluation of the differences (slope and intercept) of the independent single regression models (Kleinbaum, 2007). In addition, we performed a more practical evaluation of the biases that the application of spatial models may introduce in the temporal dimension by calculating the predicted frequency and mean size of events for total precipitation values that were one or two standard deviation away from mean of the sites, alternatively using their own temporal models or the spatial model.

Although the previous decomposition analysis describes the partition of total precipitation inputs into two simple components, it does not represent the variability or the distribution of event sizes. This variation (i.e. inequality) of event sizes was described using relative Lorenz curves (Lorenz, 1905). These curves represent the distribution of subjects (*x*-axis) and their associated accumulated quantity (*y*-axis), ordering the *x*-axis values from highest to lowest contribution in the *y*-axis. They can be represented on a relative, 0 to 1 scale, in which the unit represents the total number of subjects and the total accumulated quantity being studied, establishing a metric that allows the internal inequality of populations of different number of individuals and average quantity. These curves are typically applied to analysis of inequality and distribution of income, wealth and resources in Economics, although they have proved also very useful in Ecology (Weiner and Solbrig, 1984; Pan *et al*., 2003; Sadras and Bongiovanni, 2004). These curves quantify the inequality or asymmetry between subjects using the Gini coefficient (Gini, 1912), which is calculated as the relative difference between the integrals of the observed curve and the 1:1 line. This coefficient varies between 0 (perfect equality) and 1 (maximum inequality). In the case of precipitation events, we found that this index offers the advantages of (i) not requiring any analytical description (assumption of given distribution function) of the quantities across subjects and (ii) considers all available data, as opposed to just a given subgroup of events. This index was used here to describe precipitation patterns for every year at each site, considering events and their size as subjects and quantities, respectively. Annual Gini coefficients were compared across sites with an analysis of variance.

We searched for long-term changes and trends in annual precipitation amount, annual event frequency, annual mean event size, annual maximum mean size (ten largest ones) and decadal Gini coefficient using the Tukey test (changes among decades) and linear regression analysis (50-year trends).

In order to illustrate to what extent potential losses by evaporation and runoff would be affected by the observed shifts in precipitation structure, ignoring other relevant controls, we used fixed thresholds for each loss pathway. In the case of evaporation, a threshold of 5 mm/event was applied, considering that any event with a lower value was completely evaporated and those with a larger one lost that quantity by evaporation (Sala and Lauenroth, 1982; Golluscio *et al*., 1998). In the case of runoff, a threshold of 60 mm/event was applied, considering that runoff was null for any event smaller than this value and equalled the excess over this value for larger events. Remnant precipitation was considered available for plant transpiration (Le Houerou *et al*., 1988; Hein, 2006). On the basis of these criteria, the water potentially available for plant transpiration was determined as the ratio between effective and total precipitation.

RESULTS

Frequency and mean size of events had a similar weight dictating total precipitation shifts in central Argentina when space and time were considered together (Table I). Frequency and mean size of events scaled similarly with total precipitation (no significant difference from 0·5 slope, $p < 0{\cdot}1$) with a slight preponderance of the second component (spatial-temporal model log–log regression slopes of 0·480 and 0·520, respectively; Figure 2A, 2C insets, Table I). While providing a useful general model of event-distribution shifts in response to total precipitation in the area, this merged spatial-temporal model masked space versus time differences. The spatial model based on 50-year averages for each site also assigned similar weights to frequency and mean size of events (no significant difference from 0·5 slope, $p < 0{\cdot}1$) but with a slight preponderance of the first component (log–log regression slopes of 0·516 and 0·484, respectively; Table I). In contrast, individual temporal models showed a higher weight of mean size of events

Table I. Regression parameters (slope and intercept) and coefficients (R^2) of temporal and spatial log–log models of annual event frequency and mean annual size in response to annual total precipitation.

		Frequency			Mean size		
		Slope	$y=0$	R^2	slope	$y=0$	R^2
Temporal models	Site 1	0·394	0·396	0·37	0·606	−0·396	0·58
	Site 2	0·352[a]	0·587	0·50	0·648[a]	−0·587	0·79
	Site 3	0·300[a]	0·768	0·53	0·700[a]	−0·768	0·84
	Site 4	0·241[a]	0·943	0·29	0·759[a]	−0·943	0·79
	Site 5	0·118[a]	1·345	0·05	0·882[a]	−1·345	0·74
Spatial model		0·516	0·184	0·98	0·484	−0·184	0·97
Spatial × temporal model		0·480	0·280	0·86	0·520	−0·280	0·88

[a] Temporal model differs significantly from the spatial model ($p < 0{\cdot}05$).

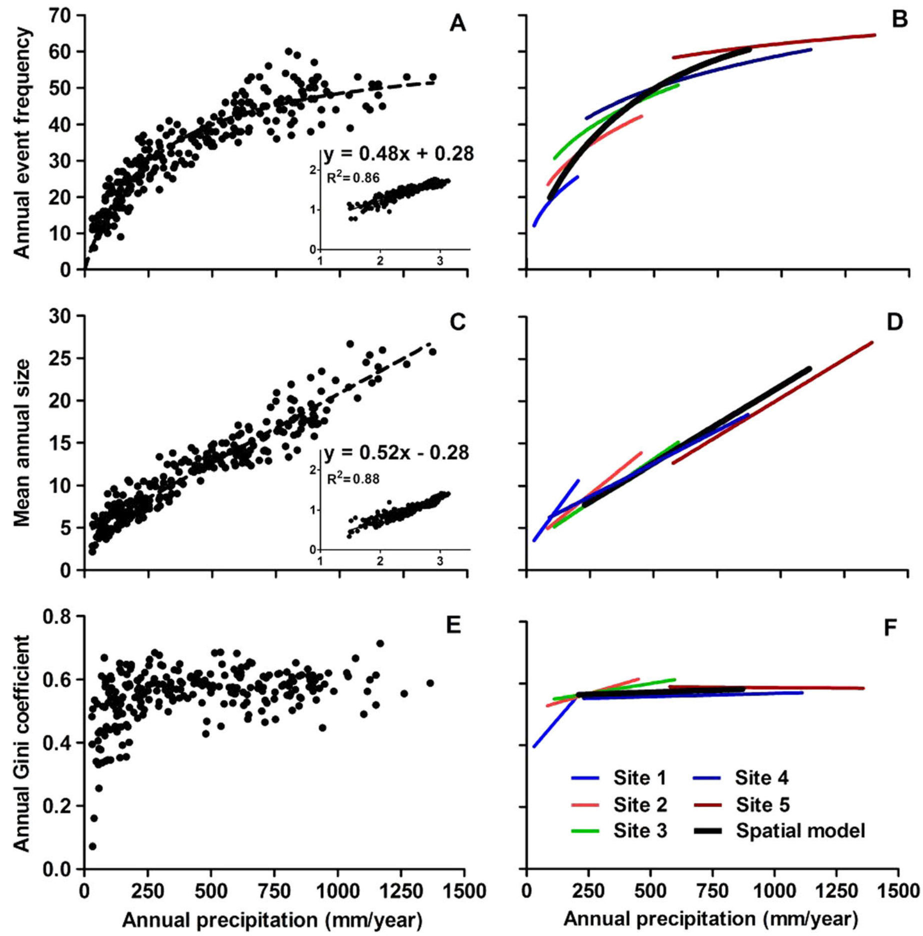

Figure 2. Annual event frequency (A and B), mean annual size (C and D) and annual Gini coefficient (E and F) as a function of annual precipitation (mm year^{-1}) for the entire period (1961–2010) and all five sites. Insets in (A) and (C) show log–log relationships. Each colour line in (B), (D) and (F) represents the function adjusted for 50 years for each site (Temporal models), and the black thick line the function adjusted to the mean values of each site (Spatial model).

driving total precipitation changes, with this preponderance growing towards the wettest sites (log–log regression slopes for mean event size raising from 0·606 to 0·882 and being higher than 0·5 in all cases with $p = 0{\cdot}067$ for site 1 and $p < 0{\cdot}05$ for the rest of the sites, Table I).

Space versus time contrasts, in the way precipitation structure scales with precipitation magnitude, call for caution when wetter or drier conditions are characterized at a given site using precipitation series from neighbouring sites along the regional gradient. The comparison of each temporal model with the spatial model showed significant differences for all sites except the driest one, showing increasing departures towards the more humid site (Table I). As an example of the maximum biases that the application of the spatial model in the temporal dimension could introduce, we show the calculations for site 5. At this site, wet years that are one and two standard deviations above the mean total precipitation (i.e. 1047 and 1222 vs 873 mm year^{-1}) have mean event sizes of 20·8 and 23·8, respectively, according to the temporal site-specific model. If the spatial model is applied to the same two values of total precipitation, estimates of mean event sizes of 18·9 mm (−9·0%) and 20·4 mm (−14·4%) are, respectively, obtained. Biases have the same magnitude and opposite sign if dry years are considered. Overall, the use of space to replace time in the analysis of precipitation structure overestimates the weight of the frequency of events and underestimates the weight of mean event size dictating total precipitation variation, ignoring the unbalance contribution of these two components to temporal total precipitation fluctuations.

The inequality of event sizes for individual years, described by the Gini coefficient on Lorenz curves, was extremely constant above 200 mm year^{-1}, averaging 0·578 ± 0·049, but became lower and more variable below 200 mm year^{-1}, reaching a value of 0·490 ± 0·110 (Figure 2E and F). Gini coefficients, however, were sensitive to the total number of events considered for their calculation, following a raising asymptotic function that stabilizes within a 25 events (data not shown). For this reason, it would not be advisable to calculate Gini coefficients for individual years that have lower than 25 events.

Very similar Lorenz curves based on the 50-year series for all sites, with values between 0·605 and 0·639, and almost overlapping lines in Figure 3B, indicated that in central Argentina, the largest tenth, quarter, and half of the events explain 42–46%, 70–73% and 91–92%, respectively, of the total precipitation (Figure 3). Interestingly, this highly constant aspect of precipitation structure changed outside of the study region. For example, in northwestern Argentina under a more tropical and monsoonal precipitation regime, Salta and Formosa stations showed 0·672 and 0·690 Gini coefficients, respectively, for the same period analysed here (data not shown).

With a few exceptions, no significant long-term trends were found for total precipitation and event distributions (Table II). We only found significant (and positive) 50-year trends for total precipitation at site 2 (2·5 mm year^{-1}, $p < 0{\cdot}01$) and site 4 (3·7 mm year^{-1}, $p < 0{\cdot}05$) accompanied by increases in the mean size of events (Table II) that were in agreement with the general predominance of this variable in explaining temporal total precipitation fluctuations. Gini coefficients did not show significant trends throughout the 50-year period or departures from the mean in any particular decade or sites.

On the basis of fixed absolute thresholds, we illustrate how precipitation structure shifts would increase the fraction of available water for plant transpiration asymptotically as total precipitation increases in space and time (Figure 4B). Spatial models, fitted to the long-term mean of each site, showed a decline, from 0·52 to 0·21, in the fraction of precipitation that would be evaporated directly from the soil. Temporal models, based on single-year values at each site, showed significant higher slopes, and hence steeper reductions in evaporative losses with increasing total precipitation ($p < 0{\cdot}05$; Figure 4A), particularly in dry sites. This results from the relative predominance of event size over event frequency explaining total precipitation fluctuations. Potential runoff losses based on the same fixed absolute threshold approach showed a higher variability along the entire precipitation gradient, with a significant increasing trend in space from 0 to 0·10 of total inputs. Being the complement of the previous two losses, potentially available water for plant transpiration displayed a steep raise from arid to semiarid condition and a smoother one towards humid ones, where it stabilized around 0·71 of total rainfall (Figure 4).

DISCUSSION

We characterized the event structure of precipitation regimes in central Argentina decomposing them into three components, namely, annual event frequency and mean annual size, which multiplied yield annual precipitation, and also their Gini coefficient, which provides a dimensionless characterization of the inequality of event sizes. We found that frequency and size increased in a balanced fashion with precipitation across space, whereas size dominated precipitation shifts through time. Size inequality patterns, instead, appeared highly constant and independent of total precipitation changes in time and space within the study region, and only changed away from its climatic boundaries. These findings have important climatic, ecologic and methodological implications.

From a climatic perspective, the observed patterns indicate that the frequency of events that a site receives every year is a relatively more constant feature of its climate than the size of those events, a trend that becomes reinforced towards more humid sites. This may be related to the characteristics of precipitation over the gradient. Convective precipitation prevails towards the west, whereas frontal precipitations become increasingly important

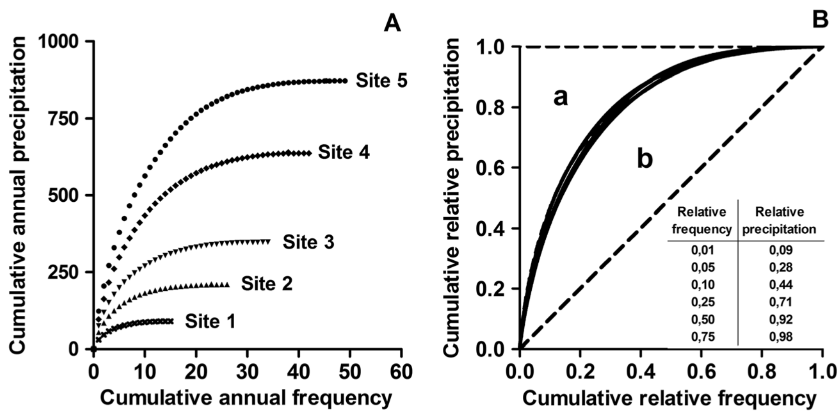

Figure 3. (A) Cumulative annual precipitation as a function of accumulated events, from the highest to the lowest, across the five study sites. (B) Lorenz curves obtained after normalizing curves in (A). Note that individual, site-specific lines are nearly overlapping. Dotted lines encompass the graphical areas used to calculated the Gini coefficient (=b/(a + b)). Gini coefficients were 0·61, 0·64, 0·64, 0·61 and 0·63, for sites 1–5, respectively. Table inset in (B) show the relative contribution of growing event percentiles to annual precipitation as obtained from the mean regional Lorenz curve.

Table II. Ten-year and long-term trends for five studied sites along the precipitation gradient.

	Site 1					Site 2					Site 3					Site 4					Site 5				
	Annual precipitation (mm)	Annual event frequency (units)	Annual mean size (mm)	Annual mean maximum size (mm)	Decadal Gini coefficient	Annual precipitation (mm)	Annual event frequency (units)	Annual mean size (mm)	Annual mean maximum size (mm)	Decadal Gini coefficient	Annual precipitation (mm)	Annual event frequency (units)	Annual mean size (mm)	Annual mean maximum size (mm)	Decadal Gini coefficient	Annual precipitation (mm)	Annual event frequency (units)	Annual mean size (mm)	Annual mean maximum size (mm)	Decadal Gini coefficient	Annual precipitation (mm)	Annual event frequency (units)	Annual mean size (mm)	Annual mean maximum size (mm)	Decadal Gini coefficient
1961–1970	76	13	5·9	30·9	0·65	155 a	24	6·3 a	39·3 a	0·65	299	32·0	9·1	62·9	0·65	558	39	14·2	70·2	0·58	781 a	47	16·9	105·6	0·63
1971–1980	89	14	6·6	31·1	0·68	199	25	7·9	41·7	0·64	372	31·0 a	11·6	72·8	0·65	615	42	14·7	87·7	0·64	881	49	18·1	108·0	0·63
1981–1990	93	18	4·9	22·9	0·54	182	25	7·3	40·5 a	0·66	381	36·0	10·1	57·3	0·63	628	44	14·2	84·8	0·60	856	50	17·2	104·5	0·63
1991–2000	87	14	6·3	22·7	0·54	279 b	28	9·9 b	66·0 b	0·66	374	37·4 b	9·8	65·8	0·63	664	44	15·2	97·9	0·60	1017 b	49	20·7	127·5	0·63
2001–2010	97	13	6·9	25·0	0·57	242	25	9·4 b	47·0	0·61	347	33·0	10·0	70·0	0·64	729	40	18·0	90·0	0·60	836	47	18·0	116·0	0·62
p-value						<0·01		<0·01								<0·05		<0·05							
Slope (year^{-1})						2·472		0·0796								3·694		0·0822							

Different letters indicate significant differences among decades ($p < 0{\cdot}05$). Slope value is presented for those cases in which a significant 50-year linear trend was detected ($p < 0.05$).

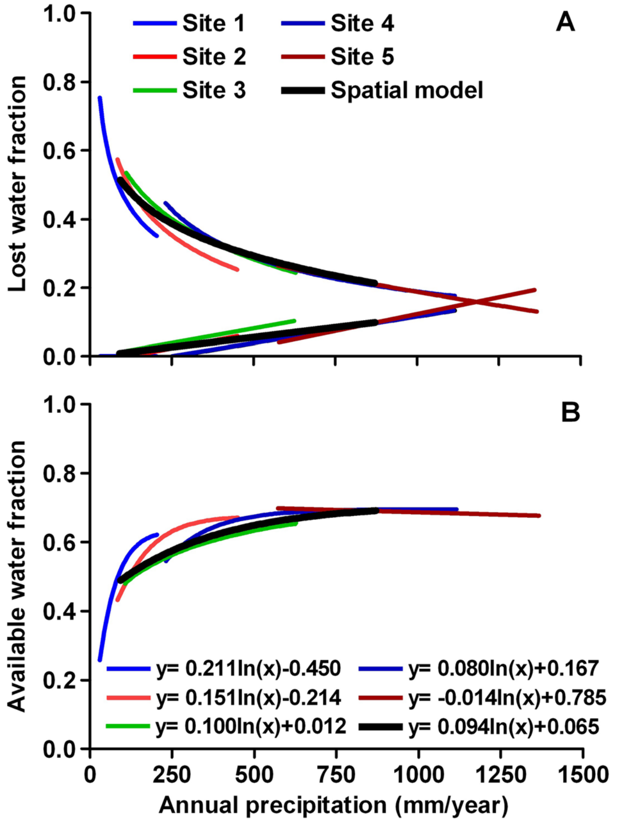

Figure 4. (A) Fraction of water lost by direct evaporation (upper lines) and runoff (lower lines) as a function of annual precipitation, for each site. The evaporation threshold was 5 mm, considering that any event with <5 mm was completely evaporated and those with >5 mm lost that quantity by evaporation. In the case of runoff, a threshold of 60 mm was considered, meaning that runoff was null for events <60 mm and equalled the excess over that value for those that were >60 mm. (B) Modelled available water for plant transpiration, as the complement of the losses presented in (A), for each site.

towards the east (Vera *et al*., 2006; INTA, 2010). Compared with high periodicity of frontal systems, convective precipitation cells have a smaller spatial scale, what yield higher temporal and spatial variability and a more stochastic nature (Nicholson, 2011). As a result of these contrasts, a growing contribution of frontal systems to total precipitation should yield a lower inter-annual variability of frequency, giving as a result a more important weight to mean event size explaining year to year shifts in total precipitation. This agrees with the observed patterns in our study.

Our relative measure of event size inequality (Gini coefficient from Lorenz curve), which is independent of the absolute number and size of events, appeared as the most conservative feature of precipitation regimes in central Argentina precipitation, perhaps being only sensitive to deep climatic shifts. With a slightly different mathematical procedure but an identical solution, Martin-Vide (2004) and Zhang *et al*. (2009) have described precipitation inequality in Spain and Southern China, respectively, finding similarly conservative patterns within broad regions but shifts across climatic domains. For Spain, more equal event distributions than those reported here were found in areas with high Atlantic influence (Gini coefficient <0·60), whereas more unequal distributions (Gini coefficient >0·64) were found for those receiving more moisture supply from the Mediterranean Sea (Martin-Vide, 2004). In Southern China, with a more tropical and monsoonal climate, inequality was even higher (Gini coefficient >0·74) (Zhang *et al*., 2009). Our own exploration of Gini coefficients in subtropical locations in Northern Argentina indicates larger values than those observed in our study region (data not shown).

The decadal and long-term analysis applied to the event distribution attributes did not indicate any of the expected effects of global warming on the precipitation regimes of central Argentina. General predictions from global atmospheric circulation models indicated larger and more unequal event sizes with anthropogenic climate change, particularly in dry regions (Schlesinger *et al*., 1990; Trenberth *et al*., 2003; IPCC, 2007). On the basis of this consensus, future primary productivity increases have been proposed and have guided experimental manipulations (Knapp *et al*., 2002; Ceballos *et al*., 2004; Bates *et al*., 2006). Our analysis did not reveal these trends over the last five decades. Only in two out of five study sites there was an increment in event sizes which, on the basis of our temporal models, we interpret as an outcome of the observed raise in annual precipitation at these sites and not an actual regime shift (Minetti *et al*., 2003; Sun *et al*., 2012).

From an ecological perspective, our analysis provides clues about what to expect regarding water availability under shifts of total precipitation. Declining precipitation inputs along the E–W gradient of central Argentina are accompanied by expected increases in potential evaporative water losses that would not be completely compensated by runoff declines. Evidence that less but larger events for a given precipitation level increase soil water availability and primary production has been provided for several dry ecosystems (Knapp *et al*., 2002; Harper *et al*., 2005; Huxman *et al*., 2005; Bates *et al*., 2006; Yahdjian and Sala, 2006; Liu *et al*., 2012; Hao *et al*., 2013). If we consider this fact and the distribution of precipitation events along aridity gradients, we should expect a more than linear drop of water availability for plants and primary production with declining total precipitation given the associated reduction in event size. However, this reasoning does not match with the universal linear trend that the primary productivity of natural ecosystems displays with precipitation along spatial gradients in dry regions of the world (Sala *et al*., 1988; Jobbágy *et al*., 2002; Del Grosso *et al*., 2008). We speculate that this linear decline of primary production with aridity may result from an offset of increasing evaporative losses by raising a use efficiency of transpired water, favoured by physiological changes and species replacement (Farquhar and Richards, 1984; Abbate *et al*., 2004; Huxman *et al*., 2004b) and suggested by previous global studies (Huxman *et al*., 2004b).

Temporal fluctuations of annual precipitation were accompanied by greater shifts in the fraction of available water than those estimated for the spatial gradient (Figure 4B). On the basis of these patterns, a stronger sensitivity of ecological processes to annual precipitation shifts would be expected in time compared with space. However, other aspects such as water storage in soils from one year to the next or structural legacies in natural vegetation may compensate this trend, as suggested by the primary production studies (Sala *et al*., 2012). Vegetation structure and litter cover are the main controls involved into the evaporation and runoff losses changes by natural processes and human management (Connolly, 1998; Weltzin *et al*., 2003; Villegas *et al*., 2010). The large effect of these losses on the available water for plant transpiration reveal the key role that the onset of no-till agriculture had in shifting the edge of dry land agriculture towards the west of our study region at the end of the 20th century (Viglizzo *et al*., 2001; Caviglia *et al*., 2004). On the other hand, in the arid end of the gradient where evaporation represents the main water loss pathway and runoff is negligible, current roller-chopping interventions, aimed to favour grasses at the expenses of woody plants in ecosystems where cultivation is considered unviable, may have part of their success in the effective retention of litter in the surface and the reduction of direct evaporation losses (Braud *et al*., 2003; Kunst *et al*., 2003; Bondeau *et al*., 2007).

We ignored seasonality effects in our analysis, an aspect of precipitation regimes that can converge with event structure influencing water availability for plants. The most important effects of seasonality are likely to be (i) the fact that a strongly seasonal regime would have a higher clustering of events and as a result shorter periods of non-rainy days between events, compared with a less seasonal regime, and (ii) the possibility of having cold versus warm season precipitation regimes, which would involve different cumulative potential evaporation for a given period of non-rainy days between events. Both components will decrease the probability of complete exhaustion of top soil moisture by evaporation before it rains again; more seasonal and cold regimes would have less direct evaporation under this rationale.

Our study provides useful methodological clues for precipitation data analysis and reconstruction in central Argentina and, more generally, along precipitation gradient with few available stations with daily data. First, we provided a basis for the reconstruction of precipitation event distributions at any given location based solely on mean annual precipitation values. The spatial functions (Figure 2B and D) can be used to calculate the mean annual frequency and mean size of events (e.g. if mean annual precipitation = 600 mm year^{-1}, then 42·1 events/year of 14·2 mm on average), what together with the average Lorenz curve (Figure 3B) provide the absolute size-frequency distribution of events (e.g. for the same case, largest 10%, next 15% – adding to one quarter – and next 25% – adding to one half – having average sizes of 62·6, 25·2 and 11·9 mm, respectively). Second, our analysis supports a cautious application of precipitation series from neighbouring stations in the region to represent the precipitation structure of wetter/drier years at a given site for which daily precipitation data are missing. This approach introduces an underestimation of mean event sizes (and at the same time an overestimation of event frequency) when wetter conditions are assumed and does the opposite when drier conditions are assumed. Finally, our results indicate that Lorenz curves can provide a robust tool to monitor profound climatic shifts in precipitation structure beyond those stemming from normal precipitation fluctuations. Our analysis did not require a priori consideration of any specific probabilistic function, but only empirical relationships based on numerical analysis of daily precipitation series.

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