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DRIVERS OF A NEW HYDROLOGICAL SCENARIO IN THE CHACO-PAMPAS BREADBASKET: THE ROLE OF CLIMATE AND VEGETATION TRENDS

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ABSTRACT. The Chaco-Pampas plain in Argentina, a key region for global food production, is experiencing a hydrological shift marked by increasing water surpluses. These surpluses are evident in rising water-table levels, increased flooding, expanded wetland and saline areas, and the formation of new rivers, all of which threaten productive systems. To investigate the causes, we analyzed long-term trends (1980-2019) in climatic variables (precipitation and reference evapotranspiration) as well as vegetation (NDVI and cropped areas) across the region, summarizing data by ecoregion unit and sub-unit and performing detailed analyses in focal zones. Our findings indicate that climatic trends do not support the generation of water surpluses. Specifically, across the region the average reference evapotranspiration increased by approximately 20 mm per decade, while precipitation remained largely unchanged except for a notable decrease (-30 mm per decade) in the Dry Chaco sub-region. In contrast, the NDVI displayed a browning trend across most of the region, suggesting a decline in the transpiration capacity of agroecosystems, largely driven by the expansion of rainfed croplands, whose area nearly tripled during the study period. At the focal sites, this browning corresponded with significant rises in water-table levels (~1 m per decade) and an intensified response to precipitation events; for a given amount of rainfall, water-tables now rise more than in previous periods. Overall, these results suggest that land cover changes have reduced ecosystem transpiration capacity, intensifying water surpluses and associated hydrological challenges, and highlight the urgent need for adaptive management strategies.

Determinantes de un nuevo escenario hidrológico en la región agrícola Chaco-Pampeana: influencia de las tendencias climáticas y de la vegetación

RESUMEN. La llanura Chaco-Pampeana en Argentina, región estratégica para la producción mundial de alimentos, está experimentando un cambio hidrológico caracterizado por un aumento de los excedentes hídricos. Estos excedentes se evidencian en el ascenso de los niveles freáticos, el incremento de las inundaciones, la expansión de humedales y áreas salinas, y la formación de nuevos ríos, todos ellos procesos que amenazan los sistemas productivos. Para investigar las causas, analizamos tendencias de largo plazo (1980-2019) en variables climáticas (precipitación y evapotranspiración de referencia) y de vegetación (NDVI y superficie cultivada) en la región, resumiendo los datos por unidad y subunidad ecoregional, y realizando análisis detallados en zonas focales. Nuestros resultados muestran que las tendencias climáticas no respaldan la generación de excedentes hídricos. En particular, en toda la región la evapotranspiración de referencia promedio aumentó aproximadamente 20 mm por década, mientras que la precipitación se mantuvo en gran medida sin cambios, salvo por una disminución notable (-30 mm por década) en el subregión del Chaco Seco. En contraste, el NDVI mostró una tendencia de disminución en la mayor parte de la región, lo que sugiere una reducción en la capacidad de transpiración de los agro-ecosistemas, impulsada principalmente por la expansión de los cultivos de secano, cuya superficie casi se triplicó durante el período de estudio. En los sitios focales, esta tendencia de disminución del NDVI se correspondió con aumentos significativos en los niveles freáticos (~1 m por década) y con una respuesta más intensa a los eventos de precipitación: para una misma cantidad de lluvia, los niveles freáticos ahora ascienden más que en períodos anteriores. En conjunto, estos resultados sugieren que los cambios en la cobertura del suelo han reducido la capacidad de transpiración de los ecosistemas, intensificando los excedentes hídricos y los desafíos hidrológicos asociados, y destacan la necesidad urgente de estrategias de manejo adaptativo.

Keywords: NDVI, Groundwater, Land-use change, Water-table, GIMMS.

Palabras clave: NDVI, agua subterránea, cambio de uso del suelo, nivel freático, GIMMS**.**

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1. Introduction

Covering nearly 1.3 million km², the Argentine Chaco-Pampas plain is one of the world’s most important food-producing regions, commonly identified as a “breadbasket” (Aguiar *et al.*, 2020). The combination of soils with few limitations and a mild climate enables rainfed agricultural production over a large portion of the area. In recent decades, there has been a strong trend toward increased grain production, with a more than threefold increase in production of the region's major crops (e.g. corn and soybean) (Whitworth-Hulse *et al.*, 2023). This growth is explained not only by improvements in management practices and genetic advances, but also by a significant expansion of the cropped area at the expense of planted pastures, natural grasslands, and native forests (Houspanossian *et al.*, 2016). Together with climate change, this profound transformation of the landscape raises questions about its potential impact on regional hydrological and consequently on the long-term sustainability of agroecosystems.

A growing number of studies has documented significant hydrological alterations in the Chaco-Pampas plain, suggesting a disruption in the water balance. For example, long-term groundwater level records show notable increases, with water-tables in some cases shifting from deep levels (>10 m), disconnected from the surface ecosystem, to very shallow levels (<2 m) in less than four decades (Alsina *et al.*, 2020). Given the extensive flatness of much of the region, these rising water- tables generally result in an increase in the frequency and intensity of floods, which now occur not only in the lowest parts of the landscape but also in higher areas that historically were not flooded (Houspanossian *et al.*, 2023). Similarly, in the more hilly parts of the region, the rapid development of new permanent flowing watercourses emerges as one of the most surprising hydrological changes (Jobbágy *et al.*, 2021b). Finally, the appearance of new saline areas, as a consequence of the now established connection between the groundwater and the ground surface, is further evidence of changes in the water balance (Diaz *et al.*, 2022). The consequences of these hydrological alterations on the region’s agricultural production are difficult to predict. On one hand, shallower water-tables tend to favor agricultural production by compensating for water deficits during dry periods (Whitworth-Hulse *et al.*, 2023). On the other hand, the expansion of flooded and saline areas would have the opposite effect by reducing the cultivable area and affecting crop yields when waterlogging and salinization of the root zone generate stress (Nosetto *et al.*, 2009).

The aforementioned hydrological changes suggest an increase in water surpluses, i.e. a greater amount of water escaping from the plant root zone and feeding both groundwater and surface water bodies. Understanding the causes behind these surpluses is crucial for predicting future hydrological trends and for implementing adaptation and/or mitigation measures in response to the new hydrological scenario. Climate changes (e.g. increased precipitation) could be one of the driving factors behind these hydrological shifts. For instance, in some regions of Argentina, increasing precipitation trends have been recorded during specific time windows (Ferrelli *et al.*, 2021), which may have enhanced groundwater recharge and contributed to rising water-tables. However, the general increase in temperatures (Barros *et al.*, 2015) would act in the opposite direction, promoting a rise in atmospheric water vapor demand (i.e., reference evapotranspiration, ETo) and, consequently, in ecosystem evapotranspiration. Nevertheless, decreasing wind speed trends recorded in certain parts of the region would counteract this effect (D'Andrea *et al.*, 2018), adding further complexity to the equation. Finally, land-use changes (e.g. conversion of native forests to agriculture) and shifts in management practices (e.g. irrigation) also have the potential to alter the water balance by modifying plant transpiration, among other mechanisms (Nosetto *et al.*, 2012).

Changes in land cover and/or agricultural management practices have the potential to affect the water balance through several mechanisms. The strongest evidence of this influence is observed when transitions between woody and herbaceous systems occur, for example, when grasslands are afforested or when native forests are replaced by annual crops. Woody systems (e.g. native forests) are characterized by structural (e.g. deeper roots, higher leaf area stability) and functional traits (e.g. lower albedo, higher aerodynamic conductance, higher salt tolerance) that enable them to maintain higher evapotranspiration rates, and consequently, lower deep drainage than the crops that typically replace them (Houspanossian *et al.*, 2013). Local studies show, for instance, that replacing dry forests of the Chaco ecoregion by annual crops triggers a deep drainage process that is absent under native forests (Marchesini *et al.*, 2017). Even more subtle changes, such as modifications in management practices (e.g., crop rotation), have the potential to alter the water balance, thereby affecting groundwater levels both locally and regionally. In this regard, both plot-level measurements and hydrological modeling suggest that replacing pastures by annual crops increases groundwater recharge and the risk of flooding (Nosetto *et al.*, 2015).

Although several local studies and modeling exercises have linked land-use changes to some of the hydrological alterations observed in the region, regional studies that simultaneously assess climate and vegetation changes and their relationship with hydrological alterations remain scarce. A recent study clearly showed an increase in the frequency of floods in the region, but it does not spatially link these events with trends in relevant climate variables (e.g., precipitation, reference evapotranspiration) or changes in vegetation cover (Houspanossian *et al.*, 2023). The spatial location of both changes in climate variables relevant to the water balance and those related to vegetation functioning is necessary for a deeper understanding of their relationship with hydrological alterations. In this regard, the use of satellite imagery, particularly the NDVI, is especially useful for analyzing long-term vegetation trends, as this index is connected not only to structural aspects (e.g. forest vs. crop) but also to functional aspects (e.g. transpiration) that are directly related to the observed hydrological alterations (Di Bella *et al.*, 2000).

The objective of this work was to spatially characterize the temporal trends of climatic and vegetation variables in the Chaco-Pampas region over the past four decades (1980-2019), and subsequently analyze their relationship with changes in water-table levels. To do this, we evaluated pixel-level trends in precipitation and reference evapotranspiration from the database provided by the Climate Research Unit (Harris *et al.*, 2020), and in vegetation using the NDVI index from the GIMMS NDVI3g product (Pinzon *et al.*, 2023) and cropped areas based on public statistics. Additionally, we summarized the information generated at both the regional and sub-region scales. In focal areas where long-term (>20 years) groundwater level data were available, we conducted a more detailed analysis of the trends and examined their relationship with the observed changes in water-table levels.

2. Materials and Methods

2.1 Study region

The study area covers the phytogeographical regions of Chaco, Espinal, and Pampas, extending between latitudes -32° and -37° and longitudes -59° and -65° (Fig. 1). The region is largely characterized by a large plain composed of aeolian and alluvial sediments, with an extremely low regional slope (<0.1%). This characteristic significantly limits runoff, which in turn reduces water loss in liquid form and makes evapotranspiration the main mechanism of water loss in the region (Jobbágy *et al.*, 2021b).

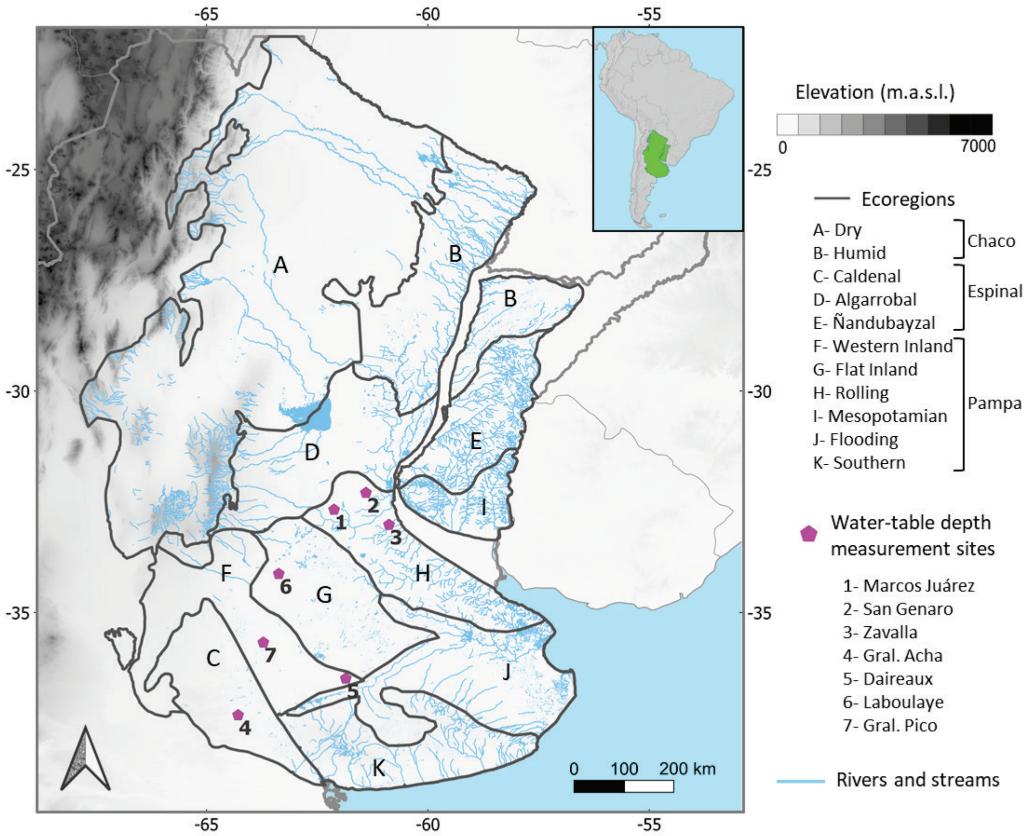

Figure 1. Map of the study area. The three ecoregions (Chaco, Espinal, and Pampas) and the sub-regions included in the study are shown. The background depicts terrain elevation (m a.s.l.), and major rivers and streams are also displayed. The locations of water-table depth measurement sites where detailed analyses were carried out are also shown.

The climate ranges from warm and humid in the northeastern part to temperate and dry at the western extreme. According to Köppen's climate classification (Köppen, 1918), most of the region falls into category Cfa, which describes a humid temperate climate with no defined dry season and hot summers. Toward the southeastern edge of the region, summers are cooler, corresponding to a Cfb climate (temperate oceanic), while still lacking a defined dry season. In contrast, in the western part of the region, precipitation becomes increasingly seasonal, concentrating in the warm season, which corresponds to a Cwa climate (temperate with dry winters and hot summers). Finally, in the far western part of the region, the climate becomes even drier and warmer, constituting a warm semi-arid climate (Bsh). The average annual precipitation (PP) ranges from 1600 mm y^{-1} in the northeastern extreme to less than 400 mm y^{-1} in the western belt (Gaitán and Biancari, 2024) (Fig. 2A). The average annual temperature varies between 23.5 °C in the northern extreme and 14.5 °C in the southern extreme of the region. Likewise, reference evapotranspiration (ETo) exceeds 1500 mm y^{-1} in the northern and western extremes, decreasing to less than 1000 mm y^{-1} in the southeastern extreme (Fig. 2B) (New *et al.*, 2002). As a result of the spatial pattern of PP and ETo, the climatic water balance is negative across most of the region, with positive values observed only in the eastern and northeastern extremes (Fig. 2C). Regarding soils, the region exhibits a variety of soil orders; Mollisols, characterized by their high fertility, are the most widespread. Additionally, in the Ñandubaizal subregion of the Espinal, fine-textured soils with high clay content (Vertisols) are found, whereas in the Dry Chaco, coarse-textured soils with a high sand content (Entisols) predominate.

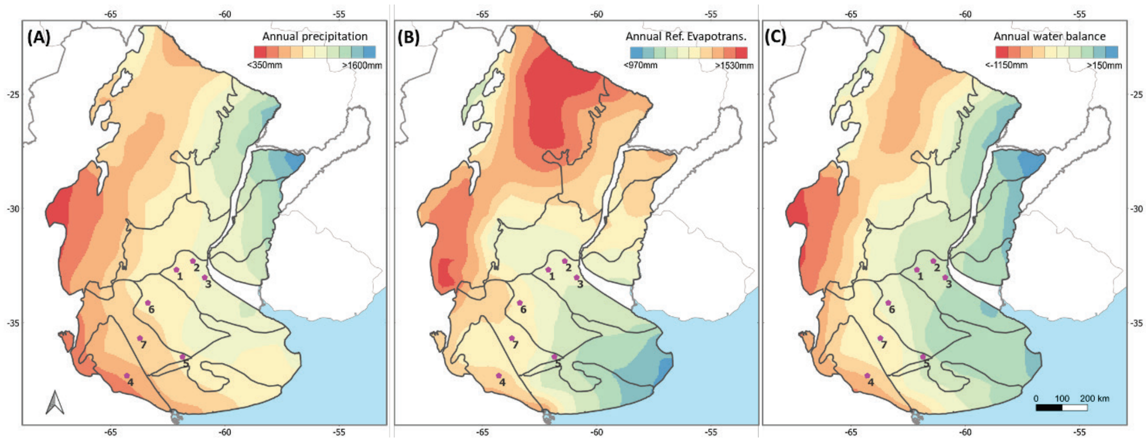

Figure 2. Climate maps of the study region. Mean annual precipitation (panel A, mm y^{-1}), reference evapotranspiration (panel B, mm y^{-1}) and climatic water balance (panel C, mm y^{-1}) are shown. The locations of water-table depth measurement sites where detailed analyses were carried out are also indicated.

In the Pampas ecoregion, the combination of a largely flat topography and a humid climate results in shallow water-tables (Alsina *et al.*, 2020). This condition favors the development of extensive and prolonged floods during periods of excessive precipitation. In contrast, in the drier Espinal and Chaco ecoregions, water-tables are located at deeper depth than in the Pampas region (Gimenez *et al.*, 2016). This situation is mainly observed under native dry forest vegetation, whereas in agricultural areas they are usually found at shallower depths (Gimenez *et al.*, 2016).

The native vegetation of the region ranges from xerophytic forests in the Chaco and Espinal ecoregions to almost treeless grasslands in the Pampas ecoregion. However, the study area has been transformed by human activity since the early 20th century, with a significant intensification in recent decades. Although native forest remains the dominant vegetation in the Chaco ecoregion, it is rapidly being replaced by annual crops and perennial pastures for livestock feeding, following a spatial pattern of deforestation "hotspots". Deforestation rates in this ecoregion rank among the highest in the world, reaching almost 500,000 hectares per year during the 2001–2012 period (Houspanossian *et al.*, 2016). In contrast, in the Pampas and Espinal ecoregions, the agricultural expansion on native vegetation has a longer history. In these areas, the most notable transformation in recent decades has been the expansion of soybean replacing perennial pastures (Nosetto *et al.*, 2015). Most crops and pastures are cultivated under rainfed conditions, with the irrigated area being negligible.

2.2. Data Sources and analysis

To analyze the possible causes of the hydrological alterations observed in the region, various climatic, hydrological, cropping, and vegetation databases were employed. Considering the availability of groundwater level data and satellite images, the study period was set as the interval between 1981 and 2019. Likewise, taking into account both the hydrological and vegetation seasonality, the working year was defined as the period from June to May of the following year.

To characterize the climate trends occurring in the study region, we used the CRU TS v. 4.05 database generated by the Climatic Research Unit (Harris *et al.*, 2020). This database contains monthly records of various climate variables for the period 1901–2020, with a spatial resolution of 0.5° x 0.5°. The variables selected for the analysis were precipitation (PP) and reference evapotranspiration (ETo), as they represent the potential supply and demand of water. ETo was calculated based on the Penman-Monteith equation (Allen *et al.*, 1998) based on mean temperature, vapor pressure, cloud cover, and wind data. Variables influencing ETo, such as wind speed, temperature, radiation, and humidity, were also analyzed but were ultimately not included in the presentation of results. Monthly values of PP and ETo were aggregated into annual values (June–May) for the period 1981–2019.

Satellite images of the NDVI index, which has been shown to be closely related to vegetation transpiration, biomass and primary productivity (Running and Nemani, 1988), were used to describe changes in vegetation over the study period. NDVI is widely recognized as a robust proxy of canopy greenness and photosynthetic activity, and has been extensively applied to infer variations in evapotranspiration and water use by vegetation across different ecosystems (Myneni *et al.*, 1997; Glenn *et al.*, 2008). The use of NDVI is particularly suitable in this study because it provides a consistent and continuous long-term record dating back to the early 1980s. Specifically, in our study region, NDVI has proven to be an effective indicator of vegetation transpiration capacity across different land covers, including crops, forests, and pastures (Contreras *et al.*, 2011; Rodriguez *et al.*, 2020; Guerra and Nosetto, 2024). In particular, the latest version of the GIMMS dataset, known as NDVI3g and derived from the NOAA satellites' AVHRR sensors, was used. This product has a temporal resolution of 15 days and a spatial resolution of 8 km, covering the period from 1981 to the present, making it an ideal tool for analyzing long-term vegetation trends. Annual composite images (May–June) were generated from the original NDVI values, excluding areas with negative values, which are typically associated with water bodies, snow, or exposed rock. To characterize changes in vegetation seasonality, we calculated annual minimum and maximum NDVI values and derived the relative range as $NDVI_{RR} = (NDVI_{max} – NDVI_{min}) / NDVI_{mean}$. This metric represents the amplitude of seasonal fluctuations in vegetation activity relative to its average annual level and is commonly used to describe ecosystem functioning (Paruelo *et al.*, 2001). All of this processing was performed using the "raster" package in R software (R Core Team, 2014).

Using annual data series for the variables of interest, Mann-Kendall analysis was performed to identify temporal trends. This analysis was carried out both at the pixel level and using the spatial averages of the ecoregions, sub-regions and focal zones described below (Fig. 1). The slope was calculated using the Theil-Sen estimator and maps of the slope were generated, allowing analysis of the spatial pattern of change by filtering out pixels without statistical significance. Additionally, for each of the regions, sub-regions, and focal zones, the percentage of pixels with significant trends was determined. At the pixel level, where thousands of independent tests are conducted simultaneously, we addressed the problem of multiple comparisons by applying the Benjamini–Hochberg False Discovery Rate (FDR) correction to the p-values obtained from the Mann–Kendall test. Only pixels with FDR-adjusted p-values < 0.10 were considered statistically significant and are displayed in the trend maps. This procedure reduces the risk of false positives while maintaining statistical power, thereby increasing the robustness of the spatial patterns described. For the analyses based on aggregated data at the regional, sub-regional, and focal zone scales, no FDR correction was applied. In these cases, the number of statistical tests was much smaller and did not pose the same problem of massive multiple testing as at the pixel level. As a result, statistical significance may be detected at the aggregated scale even in cases where only a small fraction of pixels show significant trends in the maps.

In addition to the regional and sub-regional analyses, focal zones of interest were examined in greater detail. These were sites with long-term water-table depth measurements or areas where, even without water-table depth measurements, a significant change in NDVI dynamics was observed. Based on the "NAPA" database (Alsina *et al.*, 2020), we selected seven sites distributed across different sub-regions of the Pampas that had reliable and extensive records of water-table depth measurements and exhibited different dynamics (Fig. 1) The "NAPA" database includes more than 400 water-table depth series across the Pampas region, compiled from public institutions (e.g., National Meteorological Service, National Institute of Agricultural Technology), farmers, and research groups. Measurement periods varied among sites, with the earliest records dating back to 1950. We selected a site located in General Pico (La Pampa province) with a deepening trend in the groundwater level, four sites with an upward trend in the groundwater level (General Acha, La Pampa; San Genaro and Zavalla, Santa Fe; Marcos Juárez, Córdoba provinces), and two sites with shallow water-tables and no clear trend (Daireaux, Buenos Aires; Laboulaye, Córdoba provinces) (Fig. 1). The measurement period varied among sites but spanned more than 20 years in all cases. At all sites, measurements extended until the mid-2010s, while their starting dates ranged from the late 1970s to the early 1990s.

At each site with groundwater level data, we defined areas of influence consisting of squares with sides of 20, 50, and 100 km, centered on the site location. For each buffer area, we first calculated the spatial average and then the annual mean of precipitation (PP), reference evapotranspiration (ETo), mean NDVI, and relative NDVI range. Annual values were computed over the period from June of one year to May of the following year to account for the seasonal dynamics of vegetation. This approach allowed us to assess how temporal trends in groundwater levels relate to climatic and vegetation changes. Additionally, we evaluated whether the response of the water-table to rainfall had varied throughout the study period. For this purpose, we calculated the annual change in the water-table level (i.e. ΔWT = water-table depth in May of year i minus water-table depth in May of year i-1) and analyzed its relationship with the accumulated precipitation during the year using linear regression. We fitted regression lines between annual rainfall and ΔWT for two periods: an older one (before 2000) and a more recent one (after 2000) and we examined whether the regression parameters differed between the two intervals. The rationale for selecting these periods was the marked change in agricultural land cover. Before 2000, cropland represented less than 40% of the region, whereas after 2000 it increased substantially, exceeding 60% (Guerra and Nosetto, 2024). For this analysis, we used precipitation records from the same water-table depth monitoring station, except for the San Genaro site, where we used precipitation data from a nearby station (approximately 20 km away).

From the mean NDVI slope map, we also identified seven 50 x 50 km areas that showed a clustering of pixels with marked and significant trends, which were subjected to more detailed analysis. In the Dry Chaco ecoregion, we distinguished three areas with significant decreasing trends in NDVI, although of different magnitudes. In one of these areas, native forest vegetation was mostly preserved, whereas in the other two, we observed a profound transformation toward other land uses during the study period, as evidenced by high-resolution Google Earth images (Fig. 3). Additionally, we selected two more areas with negative NDVI trends, one in the Algarrobal subregion (Espinal) and another in the Flat Inland Pampa. Agricultural statistics indicate that in recent decades, these regions have undergone a transformation in their production systems, shifting from mixed agricultural-livestock systems based on perennial pastures to purely agricultural systems with annual crops (Nosetto *et al.*, 2015). Finally, we chose two zones with positive NDVI trends, located in the Humid Chaco region and at the driest extreme of the Western Inland Pampa. For each of these zones, we calculated the following annual NDVI metrics: mean value, maximum, minimum, and relative range ($NDVI_{RR} = (NDVI_{max} - NDVI_{min}) / NDVI_{mean}$), which are indicators of ecosystem functioning (Paruelo *et al.*, 2001). We analyzed these metrics using simple and segmented linear regression to detect possible changes in the slope over the study period. Both models were compared according to the Akaike criteria (Akaike, 1974), and the best of them was selected.

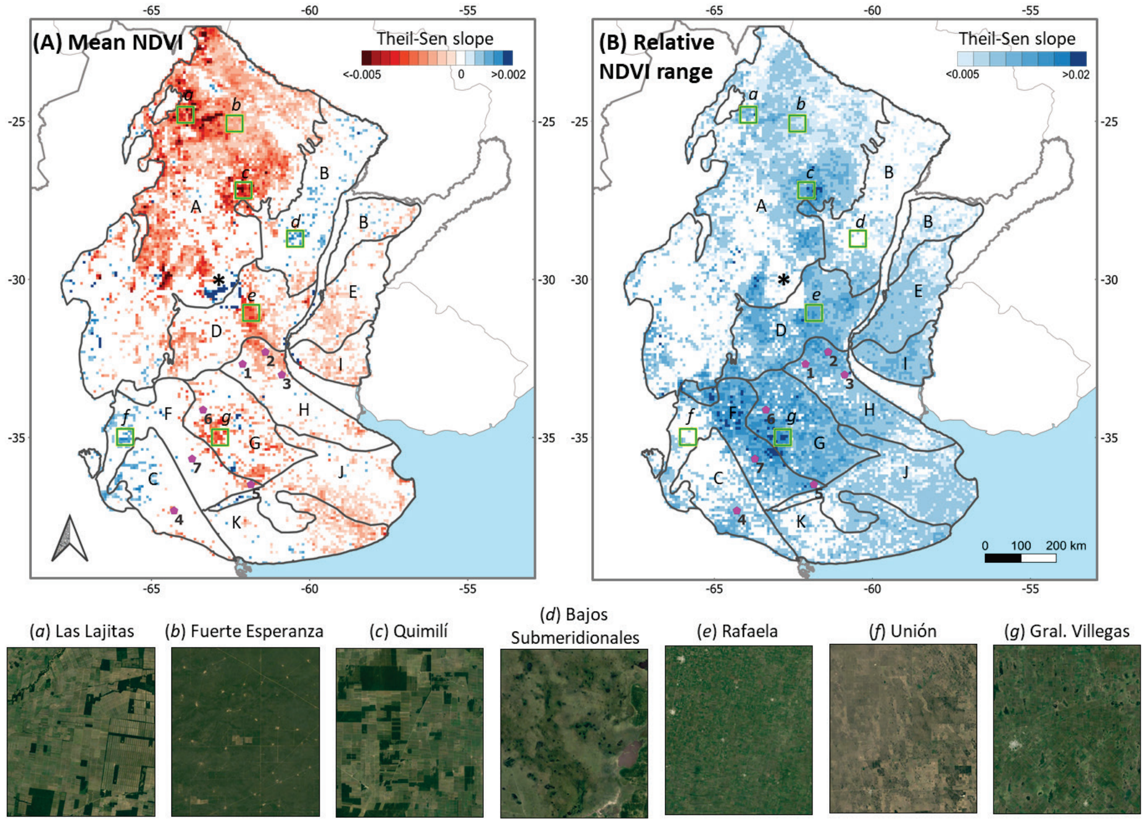

Figure 3. Trend maps of mean NDVI and relative NDVI range. Slopes were estimated using the Theil-Sen estimator, with trends detected by Mann-Kendall test between year and annual mean NDVI (panel A) and annual relative NDVI range ($NDVI_{RR} = (NDVI_{max} - NDVI_{min}) / NDVI_{mean}$)) (panel B) for the 1980–2019 period. Only pixels with statistically significant trends after Benjamini-Hochberg False Discovery Rate correction are shown (FDR-adjusted $p < 0.10$). The locations of water-table depth measurement sites (1: Marcos Juárez, 2: San Genaro, 3: Zavalla, 4: Gral. Acha, 5: Daireaux, 6: Laboulaye, 7: Gral. Pico) and areas with significant NDVI changes (a–g), where more detailed analyses were conducted are indicated. High-resolution Google Earth images at the bottom of the figure illustrate these NDVI change sites. An asterisk marks the location of the Mar Chiquita lagoon. Phytogeographic sub-regions are indicated with capital letters (A: Dry Chaco, B: Humid Chaco, C: Caldenal, D: Algarrobal, E: Ñandubayzal, F: Western Inland Pampa, G: Flat Inland Pampa, H: Rolling Pampa, I: Mesopotamian Pampa, J: Flooding Pampa, K: Southern Pampa).

To complement the NDVI-based analyses, we also characterized changes in cropped area in the region during the study period using public statistics provided by the Argentine Ministry of Agriculture, Livestock, and Fisheries (MAGyP; http://datosestimaciones.magyp.gob.ar/). These data are available annually at the administrative department level. Based on them, we calculated the total area sown with the main summer crops in the region (i.e. maize, soybean, sorghum, and sunflower). Winter crops (i.e. wheat) were excluded because they are grown almost exclusively under double-cropping systems (i.e. followed by a summer crop within the same year), which would otherwise result in double counting of cropped area. We then estimated both the total cropped area (in hectares) and the percentage of each department devoted to crops (relative to the total area of the department), using the average values for two five-year periods: the early study period (1980–1985) and the late period (2015–2020). Finally, we computed the change in cropped area between these two intervals. MAGyP data are generated from multiple sources, including field surveys, estimates from qualified advisors (e.g. information obtained from farmers, agronomists, cooperatives, and grain traders), and remote sensing.

3. Results

3.1. Regional trends

Over the last four decades, significant trends of change throughout much of the study region were identified, both in climate variables and in NDVI (Figs. 3 and 4). We detected a marked increase in ETo, with an average rise of nearly 20 mm per decade across the entire region (Figs. 4 and 5). When comparing the last decade of the study period with the first one, we noted a difference of approximately 49 mm y^{-1} in ETo at the regional level. This pattern extends across the entire study region, as all sub-regions exhibited the majority of their surface area with significant increasing trends (Table 1). The highest rates of increase in ETo were recorded in the Flooding Pampa and the Southern Pampa (> 2.2 mm y^{-1}), while the Algarrobal sub-region showed the smallest increase (1.2 mm y^{-1}).

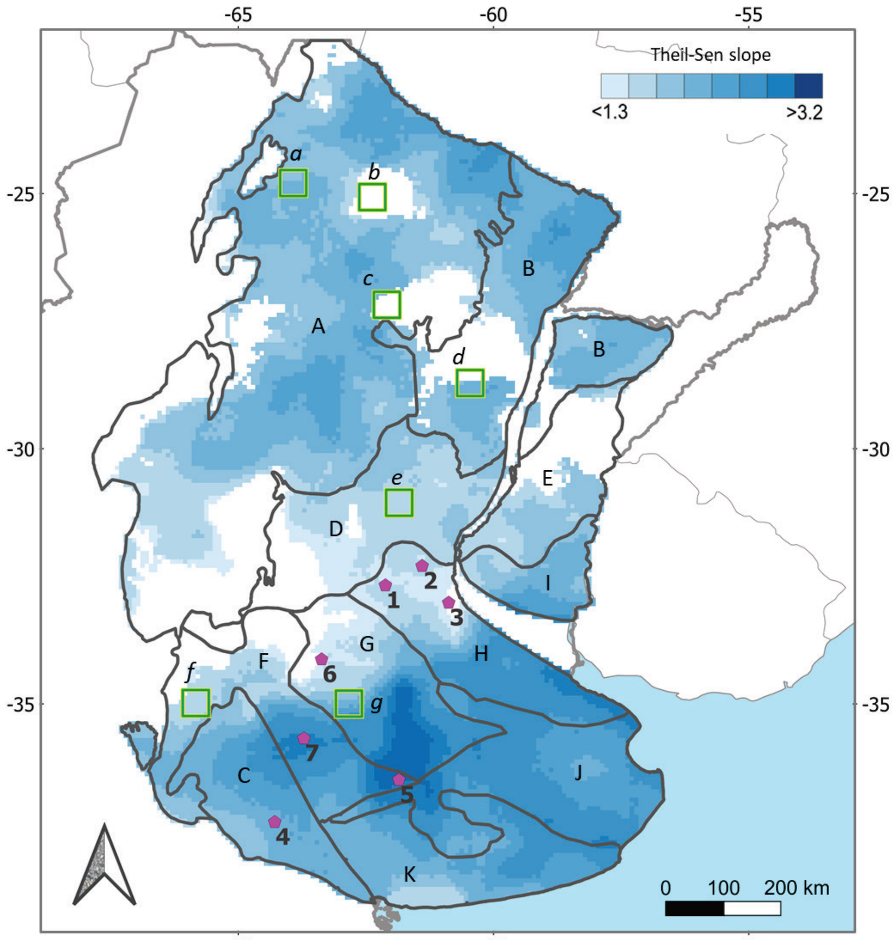

Figure 4. Trend map of reference evapotranspiration. Slopes were estimated using the Theil-Sen estimator, with trends detected by Mann-Kendall test between year and annual reference evapotranspiration (ETo) for the 1980–2019 period. Only pixels with statistically significant trends after Benjamini-Hochberg False Discovery Rate correction are displayed (FDR-adjusted p < 0.10). The locations of water-table depth measurement sites (1: Marcos Juárez, 2: San Genaro, 3: Zavalla, 4: Gral. Acha, 5: Daireaux, 6: Laboulaye, 7: Gral. Pico) and areas with significant NDVI changes (a: Las Lajitas, b: Fuerte Esperanza, c: Quimilí, d: Bajos Submeridionales, e: Rafaela, f: Unión, g: Gral. Villegas), where more detailed analyses were conducted are indicated. Phytogeographic sub-regions are indicated with capital letters (A: Dry Chaco, B: Humid Chaco, C: Caldenal, D: Algarrobal, E: Ñandubayzal, F: Western Inland Pampa, G: Flat Inland Pampa, H: Rolling Pampa, I: Mesopotamian Pampa, J: Flooding Pampa, K: Southern Pampa).

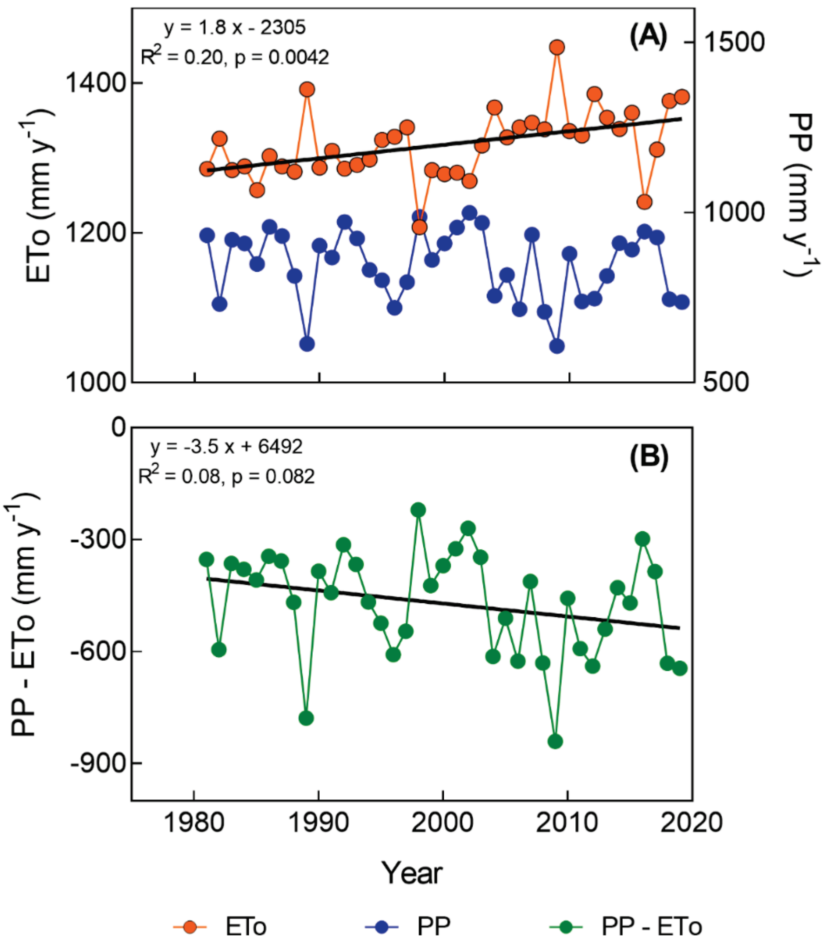

Figure 5. Temporal dynamics of reference evapotranspiration (ETo), precipitation (PP) (panel A) and water-balance (i.e. WB = PP – ETo, panel B). Annual mean values are shown for the whole study area, with significant linear regression trends indicated for PP and WB.

In contrast to ETo, precipitation (PP) did not show a significant trend of change in most of the study region (Fig. 5), except in the Dry Chaco, where we recorded a decreasing trend ($p = 0.017$, Table 1). In this sub-region, PP decreased by an average of nearly 30 mm per decade over the analyzed period (Table 1). Given that ETo also increased in that area, the climatic water balance (PP - ETo) experienced a marked decline, going from -711 mm y^{-1} in the 1981-1990 decade to -827 mm y^{-1} during the 2009-2018 period. At the scale of the whole study region, the climatic water balance also showed a trend towards greater deficit (Fig. 5, Table 1), declining from –443 mm y^{-1} in 1981–1990 to –528 mm y^{-1} in 2009-2018.

The NDVI index exhibited a significant decreasing trend in six of the eleven analyzed sub-regions (Fig. 3A, Table 1). In the Chaco ecoregion, the Dry Chaco showed the greatest decrease, with a significant negative trend identified in almost half of its area (Appendix Table A1). Furthermore, the last decade of the study recorded an average NDVI value approximately 8% lower than that of the first one (0.48 vs. 0.52 for the last and first decade, respectively). In contrast, in the Humid Chaco, areas with negative and positive trends of similar magnitude were identified (12% and 7%, respectively, Appendix Table A1). The most pronounced declines were concentrated around the towns of Las Lajitas and Quimilí, where intense deforestation occurred during the period analyzed (Fig. 3A). On the other hand, we observed that the area adjacent to the northern edge of the Mar Chiquita lagoon experienced a marked increase in NDVI (Fig. 3A), possibly due to the retreat of the water surface and its replacement by spontaneous wetland communities over the course of the study.

Table 1. Cropped area and mean Theil–Sen slope values by region and sub-region for precipitation (PP), reference evapotranspiration (ETo), water balance (PP–ETo), mean NDVI, and relative NDVI range. Cropped area is expressed in both million hectares and as a percentage of the total area, averaged for the early (1980–1985) and late (2015–2020) periods of the study. The statistical significance of temporal trends was assessed using the Mann–Kendall test, with p-values shown in parentheses.

	Theil-Sen Slope (and p-value)					**Cropped area**			
						mill. Hectares		%	
	PP	ETo	Water balance	mean NDVI	relative NDVI range	1980-1985	2015-2020	1980-1985	2015-2020
Study region	-1,13 (0.406)	1,95 (0.003)	-3,03 (0.070)	-0,0005 (0.030)	0,0050 (0.000)	10,23	27,64	9,7	25,4
Chaco	-2,93 (0.036)	1,93 (0.011)	-4,91 (0.018)	-0,0007 (0.001)	0,0029 (0.003)	1,41	5,26	2,2	8,1
Humid	-2,69 (0.435)	2,17 (0.009)	-4,51 (0.174)	0,0001 (0.743)	0,0017 (0.116)	0,36	0,62	2,4	4,1
Dry	-2,93 (0.016)	1,94 (0.009)	-4,51 (0.010)	-0,0010 (0.000)	0,0036 (0.001)	1,06	4,64	2,1	9,4
Espinal	-0,73 (0.724)	1,51 (0.019)	-2,09 (0.326)	-0,0003 (0.339)	0,0055 (0.000)	2,09	6,23	9,3	27,6
Ñandubayzal	0,25 (0.959)	1,72 (0.018)	-1,16 (0.782)	-0,0003 (0.125)	0,0048 (0.000)	0,16	0,74	2,7	12,6
Algarrobal	-1,70 (0.497)	1,25 (0.046)	-2,34 (0.406)	-0,0006 (0.052)	0,0078 (0.000)	1,58	4,91	15,1	47,1
Caldenal	-0,26 (0.860)	2,06 (0.004)	-2,03 (0.227)	0,0000 (1)	0,0033 0,0468	0,36	0,58	5,8	9,3
Pampas	0,37 (0.801)	2,26 (0.001)	-1,58 (0.450)	-0,0004 (0.144)	0,0067 (0.000)	6,72	16,15	15,4	37,1
Western Inland	-0,97 (0.529)	1,79 (0.020)	-2,55 (0.227)	0,0000 (0.840)	0,0072 (0.000)	1,20	3,24	13,4	36,3
Flat Inland	-0,16 (0.959)	2,05 (0.003)	-2,00 (0.450)	-0,0007 (0.074)	0,0096 (0.000)	1,55	4,26	20,0	54,7
Rolling	1,97 (0.421)	2,15 (0.000)	0,15 (0.959)	-0,0006 (0.026)	0,0064 (0.000)	2,40	3,94	34,4	56,6
Mesopotamian	3,35 (0.302)	2,01 (0.001)	1,23 (0.724)	-0,0006 (0.034)	0,0071 (0.000)	0,15	0,75	5,3	25,7
Flooding	0,31 (0.899)	2,44 (0.000)	-2,08 (0.421)	-0,0004 (0.102)	0,0049 (0.000)	0,72	1,88	7,3	19,3
Southern	0,41 (0.615)	2,27 (0.002)	-1,55 (0.392)	-0,0004 (0.217)	0,0047 (0.000)	0,70	2,08	9,8	29,0

In the Espinal ecoregion, the Algarrobal sub-region showed a significant decreasing trend in NDVI, while the Ñandubayzal and Caldenal sub-regions did not show statistically significant trends on average (Table 1). In the Algarrobal, the average NDVI in the last decade was 4.5% lower than in the first one (0.46 vs. 0.48). In the Ñandubayzal sub-region, a significant decrease was recorded in 28% of the area, mainly concentrated in its southern part (Appendix Table A1).

With the exception of the Southern Pampa and the Western Inland Pampa, all other Pampean sub-regions showed a significant decline in NDVI (Table 1, Fig. 3A). The most pronounced decrease was recorded in the Flat Inland Pampa, where the average NDVI in the last decade (2009–2018) was 5.3% lower than in the first (1981–1990) (0.49 vs. 0.52, respectively). Additionally, in this sub-region, as well as in the Rolling Pampa and the Mesopotamian Pampa, nearly a quarter of the area exhibited a significant decreasing trend in NDVI (Appendix Table A1).

Beyond the mean NDVI trends described above, even more pronounced changes were detected in the relative range of NDVI across almost the entire study region (Fig. 3B, Table 1). With the exception of the Humid Chaco sub-region, all other areas exhibited an increasing trend in relative NDVI range (Table 1), indicating greater seasonality in vegetation dynamics. This increase in relative range resulted from both higher annual NDVI maxima and lower annual NDVI minima (Appendix Fig. A1 and Fig. A2). Notably, no areas showed a decrease in relative range (Fig. 3B).

The area cultivated with annual crops experienced a marked expansion during the study period, with varying intensity across sub-regions and in agreement with the NDVI trends observed (Fig. 6, Table 1). Across the entire study region, cropland increased 2.7-fold, from ~10 to ~27 million hectares. In the Chaco region, cropped area expanded by 3.8 million hectares, almost entirely driven by the Dry Chaco sub-region (+3.6 million hectares), which also exhibited a significant decline in NDVI (Table 1, Fig. 3). Similarly, in the Espinal, cropped land grew by 4.14 million hectares, mainly within the Algarrobal sub-region (+3.33 million), where a significant NDVI decrease was also detected. The Pampas region showed the largest cropland expansion (+9.4 million hectares). Within this region, the Flat Inland Pampa subregion recorded the greatest absolute increase (+2.7 million hectares), accompanied by the strongest NDVI reduction among Pampas sub-regions. In relative terms, the Mesopotamian Pampa exhibited the most pronounced expansion, with a fivefold increase in cropped area (Table 1, Fig. 6).

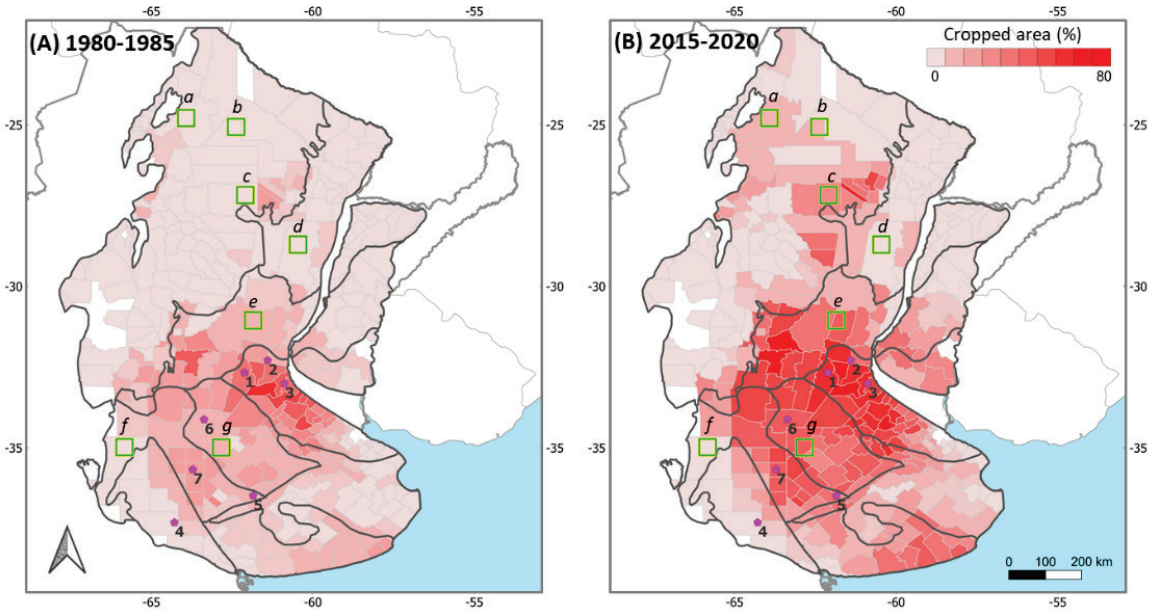

Figure 6. Cropped area with annual crops at the beginning and end of the study period. Maps show the percentage of cropped area at the departmental scale, calculated as the five-year average for the early (1980–1985, panel A) and late (2015–2020, panel B) study periods. Data correspond to the sown area of the main summer crops (i.e., maize, soybean, sorghum, and sunflower) and were provided by the Argentine Ministry of Agriculture, Livestock, and Fisheries. The locations of water-table depth measurement sites (1: Marcos Juárez, 2: San Genaro, 3: Zavalla, 4: Gral. Acha, 5: Daireaux, 6: Laboulaye, 7: Gral. Pico) and areas with significant NDVI changes (a: Las Lajitas, b: Fuerte Esperanza, c: Quimilí, d: Bajos Submeridionales, e: Rafaela, f: Unión, g: Gral. Villegas), where more detailed analyses were conducted are indicated.

The analysis of NDVI dynamics in the focal areas revealed significant changes and diverse patterns throughout the study period, helping in the interpretation of long-term trends. In the Dry Chaco sub-region, three areas were examined, all showing a decreasing NDVI trend, albeit with different magnitudes (Fig. 3). Two of these areas, located in Santiago del Estero (Quimilí site) and Salta (Las Lajitas site) provinces, experienced intense deforestation processes and cropland expansion during the analyzed period, while in the third area, referred to as Fuerte Esperanza (Chaco province), no significant changes in forest cover were observed, as indicated by Google Earth images (Fig. 3). In Quimilí and Las Lajitas, NDVI declined at a rate of 0.03 per decade, compared to a rate of 0.015 per decade in Fuerte Esperanza. Additionally, all three focal areas exhibited a significant reduction in the climatic water balance (p = 0.02

for Fuerte Esperanza, p = 0.009 for Quimilí, and p = 0.007 for Las Lajitas). In Fuerte Esperanza, NDVI showed a gradual decline throughout the study period ($p < 0.0001$), whereas in Quimilí and Las Lajitas it remained stable until around 1998 (p = 0.92 and p = 0.97, respectively), followed by a sharper decrease thereafter ($p < 0.0001$ in both cases). In fact, a segmented regression model (with two phases) provided a significantly better fit than a single linear model for these two sites, a pattern not observed in the Fuerte Esperanza focal area (Fig. 7A). Similarly, a decreasing trend was recorded in the annual minimum NDVI value, with a gradual decline in Las Lajitas and Fuerte Esperanza, and a breakpoint in the slope in Quimilí, similar to what was observed for mean NDVI (data not shown). Regarding the annual maximum NDVI value, a significant increase was detected in Quimilí, while a decrease was observed in Fuerte Esperanza, and no significant trend was found in Las Lajitas (Appendix Fig. A1 and Fig. A2). Finally, the relative range showed a significant increase in the three sites (Fig. 3B).

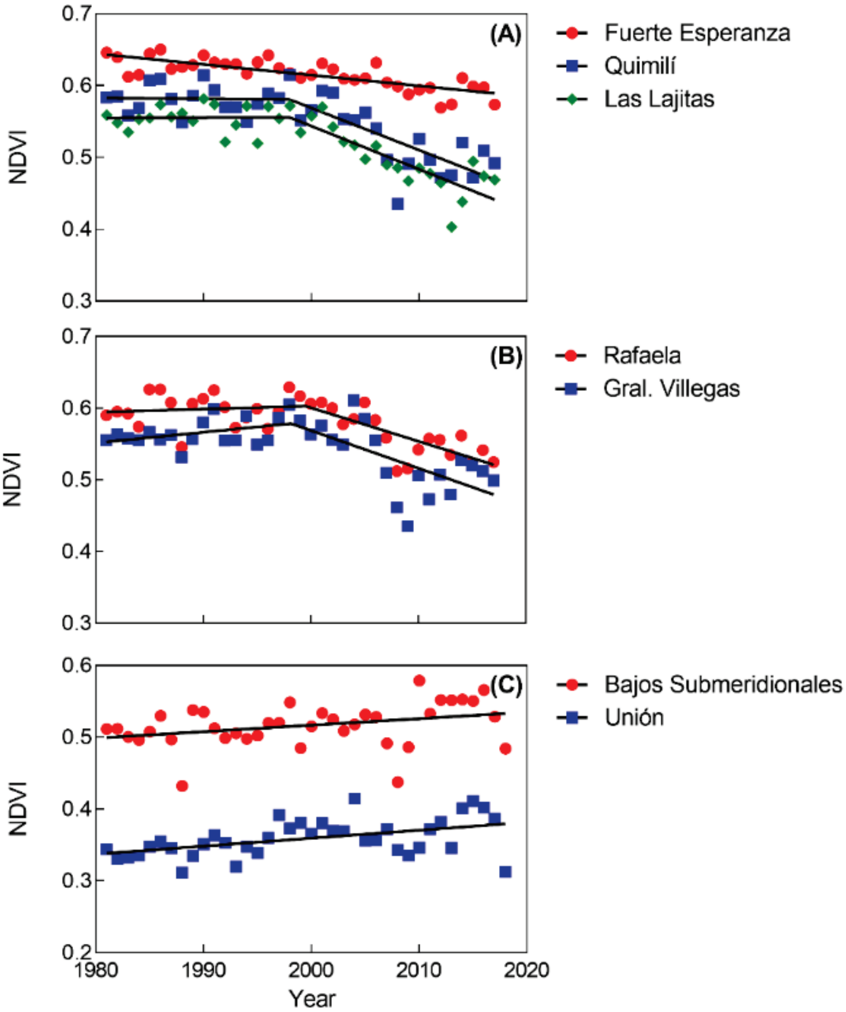

Figure 7. Temporal dynamics of NDVI in focal sites. Annual mean NDVI values throughout the analysis period are shown for each focal site analyzed in detail. Simple and segmented regression models were fitted and compared using the Akaike Information Criterion (Akaike, 1974). The best fitting model is shown. Declining NDVI trends are shown for three sites in the Dry Chaco (Fuerte Esperanza, Quimilí, and Las Lajitas) (panel A), as well as for one site in the Algarrobal sub-region (Rafaela) and another in the Flat Inland Pampa sub-region (Gral. Villegas) (panel B). In panel (C), increasing NDVI trends are displayed for two sites located in the Humid Chaco (Bajos Submeridionales) and the Western Inland Pampa (Unión).

The focal areas located in the northern Espinal (Rafaela site) and in the Flat Inland Pampa (Gral. Villegas site) exhibited a similar NDVI trajectory: a stable pattern during the early part of the study period ($p = 0.647$ and $p = 0.272$, respectively), followed by a marked decline in subsequent years ($p < 0.0001$ for both cases) (Fig. 7B). The downward trend started earlier in Rafaela (1993) than in Gral. Villegas (1998), although the rates of decline were comparable (0.03-0.05 per decade). Similar to Las Lajitas and Quimilí, a significant increase in the relative range was detected during the latter part of the study period ($p < 0.0001$) (Fig. 3B), driven by both a decrease in minimum values and an increase in maximum annual values ($p < 0.0001$ in both cases) (Appendix Fig. A1 and Fig. A2). In contrast, the focal areas of the Humid Chaco (Bajos Submeridionales site) and the Western Inland Pampa (Union site) showed moderate and gradual increases in NDVI, without notable changes in the slope ($p = 0.0409$ for Bajos submeridionales and $p = 0.0024$ for Union) (Fig. 7C). It is worth noting that the focal areas of Rafaela and General Villegas underwent a marked expansion of croplands during the study period, increasing from about 16% of the total area to more than 50% (Fig. 6). In contrast, in the Bajos Submeridionales and Union sites, the proportion of croppland remained very low throughout the study period (<3.5% in both cases) (Fig. 6).

3.2. Dynamics of water-table levels and their relationship with climatic variables and NDVI

The analysis of climatic and vegetation trends in areas with long-term water-table depth records provided insights into the potential drivers of hydrological changes in the region. In the northern sector of the Rolling Pampa, three water-table depth stations (Zavalla, Marcos Juárez, and San Genaro) with more than 20 years of records exhibited a similar pattern, showing significant upward trends in water-table levels. On average, these three sites recorded a rise of nearly 1 m per decade over the past 45 years (Fig. 8A). Similarly, the site located near General Acha showed an upward trend of 70 cm per decade over the past 30 years. These increases in water-table levels are indicative of water surpluses; however, none of these four sites showed a statistically significant increase in precipitation, either in the CRU database or in the data from local meteorological stations (Table 2).

In addition to the rise in water-table levels, a change in the response to precipitation was also observed in the Rolling Pampa sites. When comparing the response of water-table level against annual accumulated precipitation, differences were observed between recent (i.e., 2004–2016) and earlier periods (i.e., 1980–2003). While a significant relationship with annual precipitation was found in both periods, the equilibrium precipitation (i.e., the annual precipitation amount at which no net change in water-table depth would be expected) shifted toward lower precipitation levels (Fig. 9). For example, in the most recent period, the average equilibrium precipitation for the three sites was 815 mm year^{-1}, whereas in earlier periods, it was 962 mm year^{-1} ($p = 0.013$, t-test for difference in x-intercepts). In other words, approximately 147 mm less annual precipitation is now required to produce a net rise in water-table levels compared to earlier periods. This shift suggests a reduction in the actual evapotranspiration of ecosystems; however, reference evapotranspiration showed a significant upward trend at all three sites (Table 2). Additionally, the areas surrounding the three sites exhibited a declining trend in mean NDVI (statistically significant in Marcos Juárez only for the 100 km buffer) and an increasing trend in relative NDVI range. Similarly, the area surrounding the General Acha site also showed a decrease in mean NDVI and an increase in the relative NDVI range of comparable magnitude to that observed in the Rolling Pampa.

Water-table levels at Laboulaye and Daireaux sites exhibited similar behavior, showing no significant long-term trends and fluctuating at shallow depths (<3.5 m) throughout the entire recording period (Fig. 8B). Similar to the sites in the Rolling Pampa, a significant shift in the equilibrium precipitation toward lower annual values was observed at the Daireaux site when comparing recent periods (2003–2017) with earlier ones (1988–2002). The difference between the two periods was 124 mm (1055 mm vs. 932 mm year^{-1}, $p = 0.054$, t-test for difference in x-intercepts). This change in water-table depth behavior does not align with trends in reference evapotranspiration (Table 2), but it does correspond with a notable decline in mean NDVI, which decreased by up to 8% between the first and last decades analyzed (within a 20 km buffer). Conversely, no such shift in equilibrium rainfall was observed at Laboulaye ($p = 0.45$, t-test for difference in x-intercepts), nor was there a significant decrease in NDVI (Table 2).

The Gral. Pico site was the only site that showed a significant downward trend in water-table levels during the study period (Fig. 8C). No significant decrease in precipitation or changes in mean NDVI were observed in its area of influence for any of the buffer sizes analyzed. However, an increase in ETo was observed throughout the study period (Table 2). It is noteworthy that this site was the only one that did not exhibit an expansion of cultivated area during the study period, in contrast to the other six sites, which showed marked increases (Fig. 6).

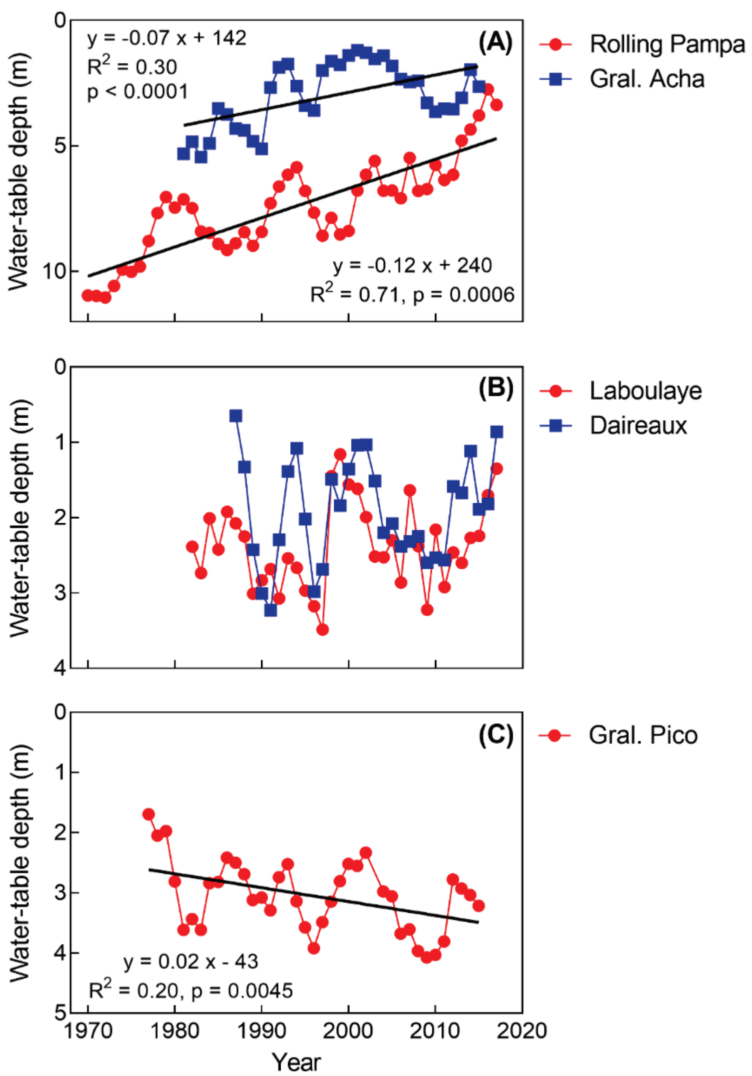

Figure 8. Temporal dynamics of water-table depth at sites in the Pampas region. In panel (A), annual mean water-table depths are shown for the Gral. Acha site and the average of three sites (Zavalla, San Genaro, and Marcos Juárez) in the Rolling Pampa. Rising water-tables were observed in both cases, with linear regression models fitted to the trends. Panel (B) shows annual means for the Laboulaye and Daireaux sites, where no significant trends were observed. In panel (C), annual mean water-table depths for the Gral. Pico site are presented, showing a deepening trend fitted with a linear regression model.

Table 2. Mean Theil–Sen slope values for each water-table depth measurement site for precipitation (PP), reference evapotranspiration (ETo), mean NDVI, relative NDVI range, and water-table depth (WT). The slopes of ETo, mean NDVI, and relative NDVI range represent the average values within three buffer areas (20, 50, and 100 km side lengths) centered on each groundwater depth measurement site. Precipitation data were recorded at the same groundwater depth monitoring station, except for the San Genaro site, where data from a nearby station (approximately 20 km away) were used. P-values are reported in parentheses.

	WT	PP	ETo			mean NDVI			relative NDVI range		
Buffer size (km)	----	----	20	50	100	20	50	100	20	50	100
Zavalla	-0,12	-0,24	1,01	1,04	1,31	-0,0007	-0,0007	-0,0007	0,0035	0,0055	0,0058
	(0.002)	(0.807)	(0.107)	(0.044)	(0.015)	(0.062)	(0.036)	(0.046)	(0.062)	(0.012)	(0.003)
San Genaro	-0,06	0,75	1,34	1,37	1,33	-0,0014	-0,0013	-0,0012	0,0107	0,0097	0,0100
	(0.074)	(0.761)	(0.026)	(0.026)	(0.020)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
M. Juarez	-0,19	-0,62	1,41	1,34	1,28	-0,0005	-0,0004	-0,0005	0,0047	0,0069	0,0072
	(0.000)	(0.824)	(0.007)	(0.008)	(0.011)	(0.406)	(0.279)	(0.078)	(0.056)	(0.000)	(0.000)
Laboulaye	-0,01	1,31	1,21	1,23	1,22	-0,0003	-0,0004	-0,0005	0,0077	0,0089	0,0099
	(0.288)	(0.575)	(0.074)	(0.070)	(0.074)	(0.529)	(0.513)	(0.144)	(0.002)	(0.000)	(0.000)
Daireaux	-0,01	-6,04	3,05	3,04	2,99	-0,0016	-0,0011	-0,0007	0,0109	0,0095	0,0084
	(0.614)	(0.141)	(0.000)	(0.000)	(0.000)	(0.002)	(0.012)	(0.092)	(0.000)	(0.000)	(0.000)
Gral. Pico	0,03	0,66	2,68	2,67	2,58	0,0001	0,0003	0,0000	0,0120	0,0094	0,0087
	(0.004)	(0.806)	(0.002)	(0.003)	(0.003)	(0.820)	(0.465)	1,0000	(0.000)	(0.000)	(0.000)
Gral. Acha	-0,07	-2,42	1,85	1,95	1,96	-0,0012	-0,0010	-0,0006	0,0065	0,0062	0,0055
	(0.000)	(0.406)	(0.008)	(0.007)	(0.004)	(0.018)	(0.082)	(0.208)	(0.000)	(0.000)	(0.002)

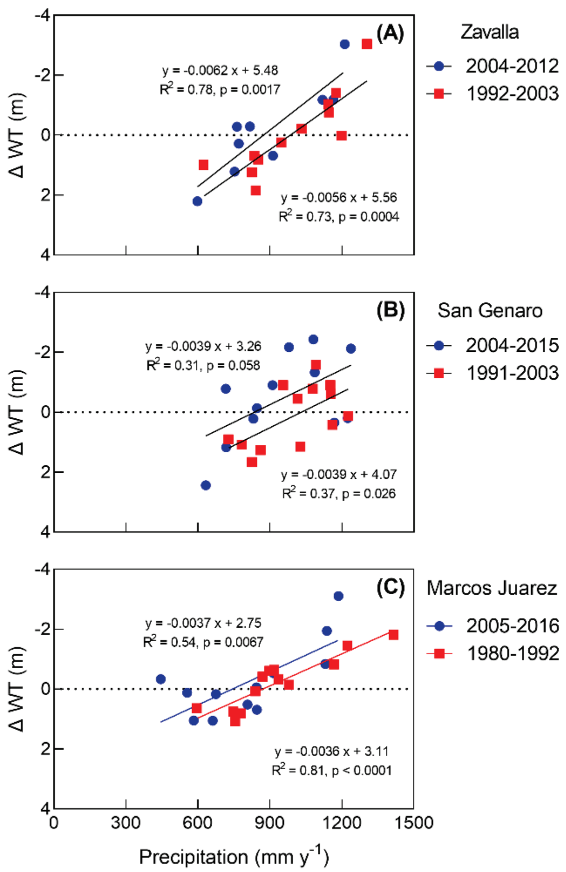

Figure 9. Water-table depth response to annual precipitation. The relationship between accumulated annual precipitation and the variation in water-table depth (Δ WT) is shown for three sites in the Rolling Pampa (A: Zavalla; B: San Genaro; C: Marcos Juárez). Linear regression models were fitted for two periods, an older and a more recent one. The point where the fitted line intersects the y=0 line represents the equilibrium precipitation.

4. Discussion

A series of hydrological changes provides converging evidence for the emergence of a new scenario in the Chaco-Pampas plain, characterized by an increasing surplus of water that is challenging the agricultural systems. This study, with a regional and long-term scope, provides novel evidence that allows us to discuss the possible causes of these changes. On the one hand, the trends observed in the climatic variables run counter to the generation of water surpluses, with a generalized increase in water demand (i.e. reference evapotranspiration, Fig. 4 and 5) and no clear precipitation trend, except for a decrease in one sub-region (Table 1). On the other hand, the satellite NDVI index, which is directly linked to the transpiration capacity of the vegetation, showed a decreasing trend throughout the study period in much of the region (Fig. 3, Table 1). Furthermore, the combined analysis of water-table level, climatic, and NDVI data in the focal areas suggests a close relationship between vegetation transpiration capacity and changes in water-table levels (Table 2). In short, when the results of this study are considered together with existing local evidence, it can be inferred with greater certainty that cropland expansion (Fig. 6) have reduced the transpiration capacity of agro-ecosystems, leading to greater water surpluses, rising water-table levels, and the intensification and expansion of floods.

Far from being a cause of water surpluses, changes in ETo may have partially mitigated the effects of vegetation changes, which would have been greater without the ETo increase. It is therefore interesting to analyze the causes of its notable upward trend (Fig. 4 and 5), already identified in previous regional studies in Argentina (D'Andrea *et al.*, 2018). The increase in ETo has been typically linked to the rise in minimum temperature (Scheff and Frierson, 2014). This increase in minimum temperature, a direct consequence of higher greenhouse gas concentrations and the subsequent reduction in nighttime radiative cooling, may affect agricultural crops in various ways, such as altering the frost-free period or decreasing their potential yield, among other impacts (Fernández-Long *et al.*, 2013; Sadok and Jagadish, 2020). Moreover, the increase in ETo itself can have significant implications for agricultural production, as it raises crop water requirements and, consequently, the risk of water stress. Notably, the increase in ETo should translate into higher actual evapotranspiration in agroecosystems (assuming a constant crop factor, Kc), and simultaneously, the rise in minimum temperature could increase the annual Kc due to a lengthening of the growing season; however, actual evapotranspiration has evolved in the opposite direction (lower NDVI), thereby overcompensating for the increase in ETo.

Precipitation did not exhibit an overall increasing trend across the region; in fact, a decline was observed in the Chaco region (Table 1), suggesting that, at least directly, it does not account for the generation of water surpluses. Nonetheless, it is worth noting that prior to our analysis period, parts of the region, mainly the western sector, experienced an increase in precipitation that extended until approximately the mid-1970s (Fernández-Long *et al.*, 2013). This increase encouraged farmers to expand the agricultural frontier into drier areas by establishing rainfed annual crops, replacing livestock systems based on perennial pastures, grasslands, and native forests (Viglizzo and Frank, 2006). As detailed later, this cropland expansion (Fig. 6), evidenced in our study by the decline in mean NDVI and the increase in relative NDVI range (Fig. 3, Table 1), is closely associated with lower ecosystem transpiration and the generation of water surpluses (Santoni *et al.*, 2010; Nosetto *et al.*, 2012). Therefore, while recent precipitation may not have had a direct effect on the water surpluses observed, it is possible that in earlier periods it indirectly contributed by promoting agricultural expansion over lands with perennial vegetation.

A significant part of the study region showed a marked decrease in mean NDVI, a process commonly referred to as "browning", which suggests various transformations in local ecosystems (Fig. 3A, Table 1). NDVI trends have been linked to different processes, such as land use changes (Baldi *et al.*, 2008), ecological responses to climate change (Pettorelli *et al.*, 2005), phenological changes (White *et al.*, 2009), or desertification (Symeonakis and and Drake, 2004), among others. In our study, we interpret that much of the NDVI decline is primarily due to cropland expansion (Fig. 6) (Baldi *et al.*, 2008).In particular, the NDVI declines observed in the Pampas and Caldenal, areas where native vegetation was already limited at the beginning of the study period, are mainly attributed to the replacement of mixed agricultural-livestock systems, based on a rotation of perennial pastures and annual crops, with pure annual crop systems (Jobbágy *et al.*, 2021a). It is noteworthy that annual crops have an NDVI approximately 15% lower than that of mixed systems (Nosetto *et al.*, 2015) and have tripled their area in central Argentina during the study period, reaching about one third of the area (Fig. 6). The more pronounced decrease in the minimum NDVI values and the increase in the relative range (Fig. 3, Appendix Fig. A1) also support the notion of a shift toward annual crops, as these leave the soil bare for part of the year and then show a peak in greenness during the summer, resulting in the observed pattern (Nosetto *et al.*, 2012; Jobbágy *et al.*, 2021a). On the other hand, in the Dry Chaco ecoregion, the most pronounced NDVI declines are also associated with the replacement of native forests by annual crops (Fig. 3 and Fig. 6). In contrast, the less pronounced declines, where such a transformation is not evident, could be due to the decreasing rainfall trend (Table 1), combined with processes of native forest degradation such as selective logging of valuable species or charcoal production.

NDVI increase trends, commonly referred to as "greening", were identified in our study area; however, these trends were more spatially localized and less widespread (Fig. 3). This phenomenon has been observed in other regions of the world in response to different causes. For example, in the Sahel it has been associated with precipitation variability (Anyamba and Tucker, 2005), while in the North American tundra and boreal regions it has been linked to increased temperature and atmospheric CO_2 concentration, which have extended the growing season and photosynthetic activity (Goetz *et al.*, 2005). In our region, clear increasing trends were detected in the Caldenal ecoregion and in the western part of the Inland Pampa, possibly due to a process of woody encroachment observed in recent decades (Chaneton *et al.*, 2012). This increase in woody vegetation cover is occurring in areas historically covered by woody vegetation as well as in grassland areas and is attributed to a combination of environmental and anthropogenic factors (González-Roglich *et al.*, 2015). A significant increases in NDVI were also recorded in the Bajos Submeridionales area (Fig. 3), although the explanation in this case is more complex; perhaps the atmospheric increase in CO_2 contributes to this pattern, as has been observed in other ecosystems (Rifai *et al.*, 2022).

The browning observed in the region may be associated with a reduced transpiration capacity of the ecosystems, which in turn could generate the documented water surpluses. This direct relationship between NDVI trends and hydrological alterations at the regional scale has already been identified elsewhere. In Uruguay, for example, greening in afforested catchments was linked to a decrease in stream flow (Cano *et al.*, 2023). Conversely, cases where browning explains the opposite process are rarer. However, a recent study performed within our study region showed an association between a decline in NDVI, as a result of agricultural expansion, and an increase in water yield in a heavily transformed catchment (Guerra and Nosetto, 2024). In our analysis, we directly related the decrease in NDVI to a reduction in ecosystem evapotranspiration, a pattern supported by numerous local studies based on field measurements and hydrological modeling (Nosetto *et al.*, 2012; Nosetto *et al.*, 2015; Nosetto *et al.*, 2020; Rodriguez *et al.*, 2020; Jobbágy *et al.*, 2021b). In fact, the spatial characterization of the NDVI decline and its relation to hydrological changes is one of the most valuable and novel contributions of this work.

The new hydrological scenario, characterized by higher water surpluses, is reflected not only in the rise of water-tables but also in changes in their response to rainfall (Fig. 9). The equilibrium precipitation, defined as the annual amount of precipitation that does not cause changes in the water-table depth, has shifted toward lower values. It is interesting to note that the magnitude of this shift (~130 mm) is similar to the difference in evapotranspiration between annual crops and perennial vegetation (Nosetto *et al.*, 2012; Nosetto *et al.*, 2015), reinforcing the hypothesis that the reduced evapotranspiration capacity associated with agriculture is causing the water surplus. This lower equilibrium precipitation means that smaller amounts of rainfall can trigger changes in water-table levels, increasing the risk of flooding, altering aquifer recharge, and creating a more sensitive hydrological response to rainfall events.

Elevated groundwater levels and, more generally, an increased water stock in the region could boost water outputs both through enhanced ecosystem evapotranspiration and increased streamflow from the few rivers draining the area, establishing a negative feedback between these processes. Given the extremely flat topography (slope <0.1%), liquid water outputs are severely limited and represent only a small fraction of the regional water balance (<10% of annual precipitation) (Kuppel *et al.*, 2015). Nonetheless, this feedback already appears to be operating, as evidenced by an increase in water yield in a basin undergoing significant agricultural expansion, with no change in precipitation (Guerra and Nosetto, 2024). Moreover, an increase in crop transpiration in response to rising groundwater levels has been observed both at the plot scale (Nosetto *et al.*, 2009) and at the regional scale (Whitworth-Hulse *et al.*, 2023). However, this positive influence of groundwater on crops does not seem to have offset the widespread browning trend that we observed. It is possible that farmer's management of agroecosystems has not yet adapted to the new hydrological conditions, making it crucial to implement flexible strategies for agricultural intensification (Jobbágy *et al.*, 2021a; Gimenez *et al.*, 2024). In conclusion, these findings highlight the complex interplay between hydrological dynamics and agro-ecological responses, and the need for adaptive management strategies that optimize water use and mitigate the adverse effects of the browning trend in the region.

5. Conclusions

This study allowed us to analyze climate and vegetation trends, as well as their hydrological effects, in the Chaco-Pampas plain over the past four decades, providing new insights into changes in local ecosystems. The results indicate that the alterations in the water balance are not directly attributable to climatic variations, but are deeply linked to changes in land use and vegetation cover. The reduction in NDVI, particularly in areas converted to annual crops, suggests a decrease in the ecosystems' transpiration capacity, which in turn appears to be the primary driver of rising groundwater levels and associated hydrological alterations, such as increased water yield and intensified flooding. Furthermore, although the recent increase in reference evapotranspiration might have partially mitigated the impact of reduced vegetation transpiration, it has not been sufficient to offset the overall trend toward water surpluses. The shift in equilibrium precipitation values further corroborates the hypothesis that crops expansion, by lowering the transpiration capacity of ecosystems, are exacerbating water surplus conditions. In summary, our findings underscore the complex interplay between climatic variables, vegetation dynamics, and hydrological responses. They also highlight the urgent need for adaptive management strategies that not only optimize water use but also address the negative impacts of the browning trend on regional hydrology and agricultural sustainability.

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Appendix

Table A1. Percentage of pixels with significant positive (+) and negative (-) temporal trends for reference evapotranspiration (ETo), mean NDVI, and relative NDVI range. Results are not shown for precipitation (PP) or water balance (PP–ETo), as no pixels exhibited significant trends. Statistical significance was assessed using the Mann–Kendall test, and pixel-level trends were considered significant only if they passed the Benjamini–Hochberg False Discovery Rate (FDR) correction (FDR-adjusted p < 0.10).

	ETo		mean NDVI		relative NDVI range	
	+	-	+	-	+	-
Study region	82	0	3	30	65	0
Chaco	75	0	3	39	52	1
Humid	78	0	7	12	43	1
Dry	74	0	2	48	55	0
Espinal	76	0	4	22	74	0
Ñandubayzal	56	0	2	28	88	0
Algarrobal	73	0	2	31	86	0
Caldenal	100	0	7	4	43	0
Pampas	94	0	3	21	79	0
Western Inland	80	0	9	5	69	0
Flat Inland	90	0	2	27	97	0
Rolling	98	0	1	22	85	0
Mesopotamian	100	0	2	35	92	0
Flooding	100	0	1	24	81	0
Southern	100	0	2	24	64	0

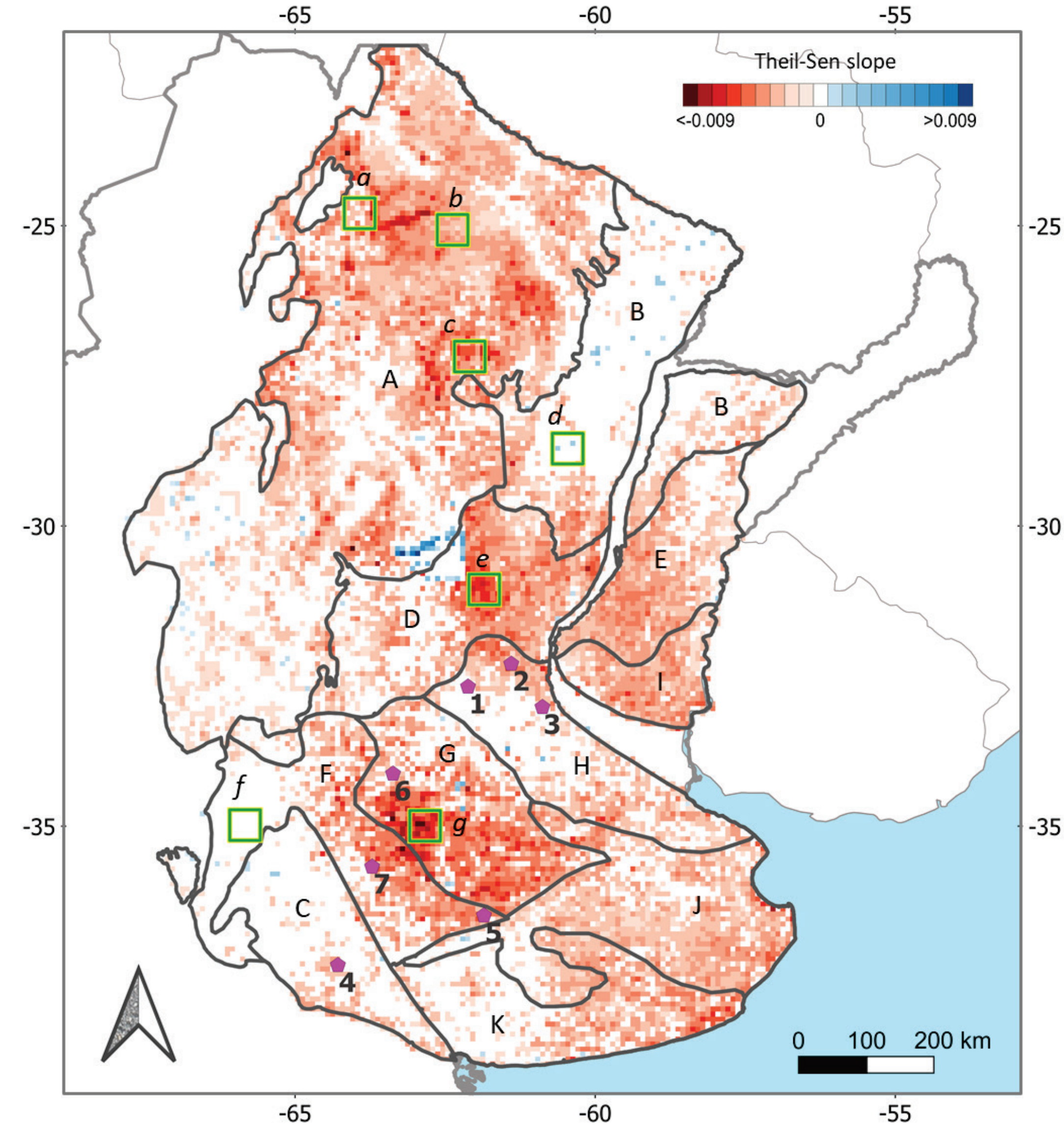

Figure A1. Trend map of annual minimum NDVI. Slopes were estimated using the Theil-Sen estimator, with trends detected by Mann-Kendall test between year and annual minimum NDVI for the 1980–2019 period. Only pixels with statistically significant trends after Benjamini-Hochberg False Discovery Rate correction are shown (FDR-adjusted p < 0.10). The locations of water-table depth measurement sites (1: Marcos Juárez, 2: San Genaro, 3: Zavalla, 4: Gral. Acha, 5: Daireaux, 6: Laboulaye, 7: Gral. Pico) and areas with significant NDVI changes (a–g), where more detailed analyses were conducted are indicated. Phytogeographic sub-regions are indicated with capital letters (A: Dry Chaco, B: Humid Chaco, C: Caldenal, D: Algarrobal, E: Ñandubayzal, F: Western Inland Pampa, G: Flat Inland Pampa, H: Rolling Pampa, I: Mesopotamian Pampa, J: Flooding Pampa, K: Southern Pampa).

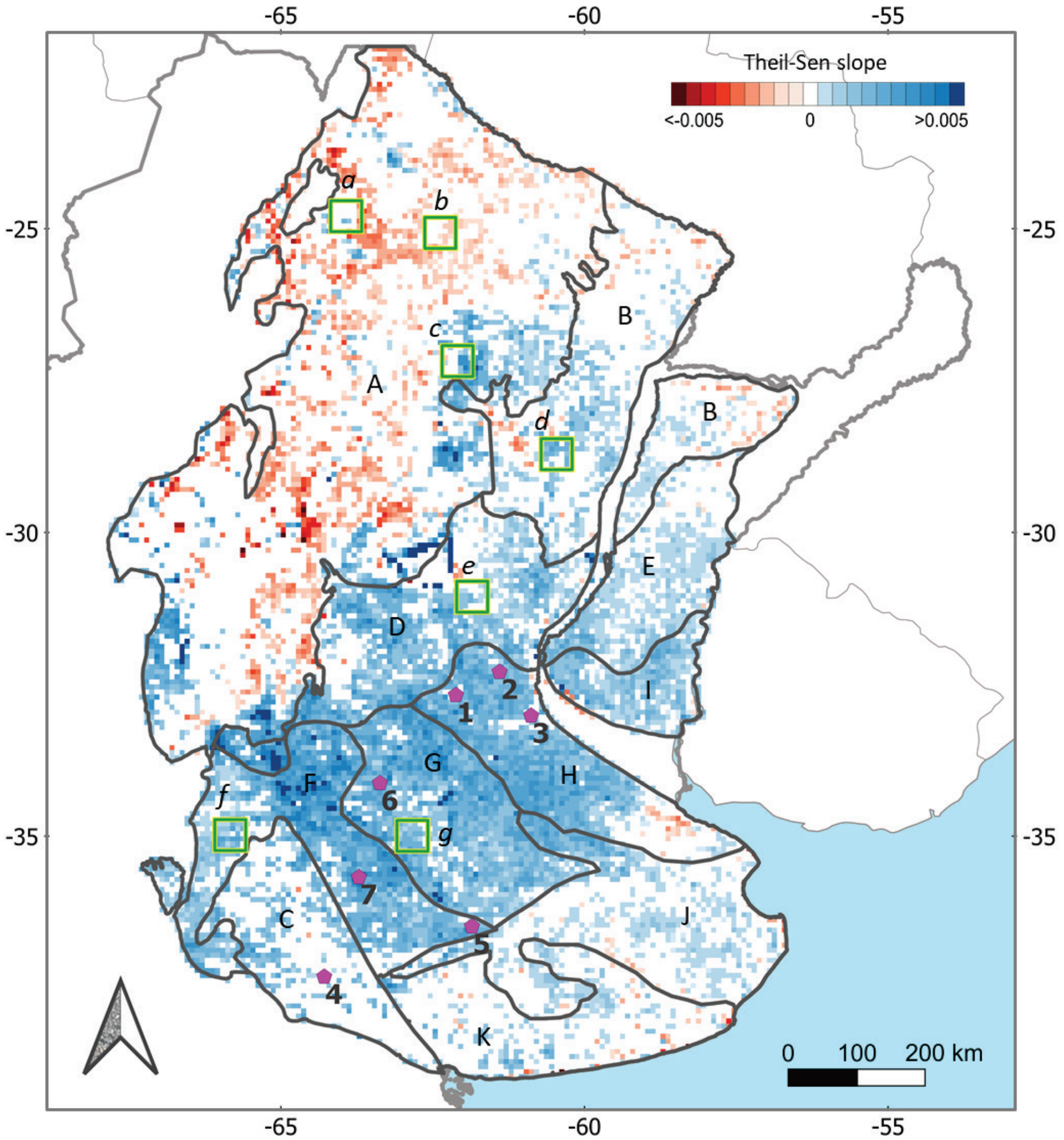

Figure A2. Trend map of annual maximum NDVI. Slopes were estimated using the Theil-Sen estimator, with trends detected by Mann-Kendall test between year and annual maximum NDVI for the 1980–2019 period. Only pixels with statistically significant trends after Benjamini-Hochberg False Discovery Rate correction are shown (FDR-adjusted p < 0.10). The locations of water-table depth measurement sites (1: Marcos Juárez, 2: San Genaro, 3: Zavalla, 4: Gral. Acha, 5: Daireaux, 6: Laboulaye, 7: Gral. Pico) and areas with significant NDVI changes (a–g), where more detailed analyses were conducted are indicated. Phytogeographic sub-regions are indicated with capital letters (A: Dry Chaco, B: Humid Chaco, C: Caldenal, D: Algarrobal, E: Ñandubayzal, F: Western Inland Pampa, G: Flat Inland Pampa, H: Rolling Pampa, I: Mesopotamian Pampa, J: Flooding Pampa, K: Southern Pampa).