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Fires in the South American Chaco, from dry forests to wetlands: response to climate depends on land cover

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Abstract

Background Wildfires represent an important element in the bio-geophysical cycles of various ecosystems across the globe and are particularly related to land transformation in tropical and subtropical regions. In this study, we analyzed the links between fires, land use (LU), and meteorological variables in the South American Chaco (1.1 million km²), a global deforestation hotspot and fire-exposed region that has recently attracted greater attention as the largest and one of the last tropical dry forests in the world.

Results We found that the Dry Chaco (73% of the total area of Chaco) exhibits a unimodal fire seasonality (winter-spring), and the Wet Chaco (the remaining 23%) displays a bimodal seasonality (summer-autumn and winter-spring). While most of the burnt area (BA) was found in the Wet Chaco (113,859 km²; 55% of the entire BA), the Dry Chaco showed the largest fraction of forest loss (93,261 km²; 88% of the entire forest loss). Between 2001 and 2019, 26% of the entire Chaco's forest loss occurred in areas with BA detections, and this percentage varies regionally and across countries, revealing potential connections to LU and policy. Argentina lost 51,409 km² of its Chaco tree cover, surpassing the forest losses of Paraguay and Bolivia, and 40% of this loss was related to fire detections. The effect of meteorological fluctuations on fuel production and flammability varies with land cover (LC), which emerged as the principal factor behind BA. While wet areas covered with herbaceous vegetation showed negative correlations between BA and precipitation, some dry regions below 800 mm/year, and mostly covered by shrublands, showed positive correlations. These results reveal the two different roles of precipitation in (a) moisture content and flammability and (b) production of biomass fuel.

Conclusions As fires and deforestation keep expanding in the South American Chaco, our study represents a step forward to understanding their drivers and effects. BA is dependent on LC types, which explains the discrepancies in fire frequency and seasonality between the Wet and Dry Chaco subregions. The links between fires and deforestation also vary between regions and between countries, exposing the role of anthropic forcing, land management, and policy. To better understand the interactions between these drivers, further studies at regional scale combining environmental sciences with social sciences are needed. Such research should help policy makers take action to preserve and protect the remaining forests and wetlands of the Chaco.

Keywords Wildfires, Fire regime, Burnt area, Gran Chaco, CCI Fire, Land cover, Deforestation, Dry tropical forests, Wetlands

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Resumen

Antecedentes Los incendios forestales representan un elemento importante en los ciclos bio-geofísicos en varios ecosistemas alrededor del mundo, y están particularmente relacionados con la transformación en el uso de la tierra (LU) en regiones tropicales y subtropicales. En este estudio, analizamos las relaciones entre los incendios, el LU y las variables meteorológicas en la región del Chaco Sudamericano (1,1 millón de km²), un foco global de deforestación y expuesto a incendios que ha concitado recientemente la atención por ser uno de los más grandes y últimos bosques tropicales secos del mundo.

Resultados Encontramos que el Chaco seco (73% del área total del Chaco), exhibe una estacionalidad unimodal en cuanto a los incendios (en invierno-primavera), mientras que el Chaco húmedo (el restante 23%) muestra una estacionalidad bimodal (verano-otoño e invierno-primavera). Aunque la mayor parte del área quemada (BA) se encuentra en el Chaco húmedo (113.859 km²; 55% del total del BA), el Chaco seco muestra la fracción más grande de la pérdida de bosques (93.261 km²; 88% de la pérdida de bosques). Entre 2001 y 2019, el 26% del total de pérdida de bosques del Chaco ocurrió en áreas que fueron detectadas como quemadas, y este porcentaje varió regionalmente y entre países, revelando conexiones potenciales con el LU y las políticas de uso. La Argentina perdió 51.409 km² de la cobertura arbórea en el Chaco, sobrepasando las pérdidas de bosques en Paraguay y Bolivia, y el 40% de estas pérdidas fue relacionada con detecciones de incendios. El efecto de las fluctuaciones meteorológicas e inflamabilidad varió con la cobertura del suelo (LC), que emergió como el factor principal luego de BA. Mientras que las áreas húmedas cubiertas por vegetación herbácea mostraron correlaciones negativas entre BA y precipitación, algunas regiones secas con menos de 800 mm/año –la mayoría de ellas cubiertas por arbustos– mostraron correlaciones positivas. Estos resultados revelan los dos roles diferentes de la precipitación en a) contenido de humedad e inflamabilidad, y b) producción de biomasa combustible.

Conclusiones A medida que las deforestaciones continúan expandiéndose en el Chaco sudamericano, nuestro estudio representa un paso más hacia el conocimiento de sus causas y efectos. Las BA son dependientes de los tipos de LC, lo que explica las discrepancias en la frecuencia y estacionalidad del fuego entre las subregiones secas y húmedas del Chaco. Las relaciones entre fuegos y deforestación también varían entre regiones y países, lo que expone los roles del factor antrópico, el manejo de la tierra y las políticas de manejo. Para entender mejor las interacciones entre esos factores, son necesarios más estudios a escala regional, que combinen las ciencias ambientales con las sociales. Estas investigaciones podrían ayudar a los tomadores de decisiones a implementar acciones para preservar y proteger los bosques y áreas húmedas del Chaco.

Background

Wildfires represent an important element in the biogeophysical cycles of various ecosystems across the globe (Bowman et al. 2009; Archibald et al. 2013) as they create disturbances that significantly alter landscapes, from dry savannas (Bucher 1982; Lacey et al. 1982) to wetlands (Kotze 2013). These disturbances have major environmental impacts by affecting the carbon fluxes and emissions (Crutzen and Andreae 1990), the vegetation dynamics through biomass burning and recovery (Bond and Archibald 2003; Nolan et al. 2021), and the energy and water cycles through the consequential changes in land cover's (LC) surface albedo and evapotranspiration (Lasslop et al. 2019). During the last decades, fire regimes of several global regions began to present significant alterations due to climate change and human land-use (LU) pressure (Giglio et al. 2013). Apart from the climatic impacts, extreme fire events occurring in tropical and subtropical forests have been shown to represent a great negative effect on biodiversity (Rappaport et al. 2018;

Staal et al. 2020), with high rates of tree mortality and gradual conversion of the landscape to savanna-like ecosystems and agricultural lands (Levine et al. 2016; Brando et al. 2020; Saatchi et al. 2021).

While lightning remains the primary natural cause of fire ignition (Jones et al. 2022), human activity emerged as the dominant direct and indirect origin of wildfires for several ecosystems worldwide (Bowman et al. 2011), with examples in Africa: Archibald et al. (2012); in North America: Taylor et al. (2016); and in South America: Argañaraz et al. (2015a, b) and Andela et al. (2022). For instance, Jones et al. (2022) show that in Southern Amazonia, almost 70% of the burnt area (BA) exhibited significant positive correlations with population density, highlighting the anthropogenic origin of fires in the region.

After an ignition source, the meteorological conditions (Abatzoglou et al. 2019; Bedia et al. 2015) and the state of the fuel (Archibald et al. 2018) are the main determinants of the duration, intensity, and expansion

of fires. In this way, climate directly controls the spread of fires through weather and moisture conditions of the fuel and indirectly through ecosystem productivity and LC (Jones et al. 2022). Global warming is expected to alter the fire regimes by expanding global fire seasons (Jolly et al. 2015) and increasing the intensity and size of fires due to the promotion of available biomass and fuel drying (Hantson et al. 2017).

Earth Observation (EO) satellite missions and Remote Sensing (RS) allow scientists to monitor global fires from space, and several products mapping BA, radiative power, or carbon emissions are available (Chuvieco and Congalton 1989; Jones et al. 2022). There has been a significant increase in the availability of global BA products in recent years, derived from sensors with a high temporal resolution, such as MODIS (Moderate Resolution Imaging Spectroradiometer), MERIS (Medium Resolution Imaging Spectrometer), or VEGETATION. These sensors provide frequent temporal coverage, with daily or near-daily observations, which allows the detection of burning events in almost real-time. However, the spatial resolution of these sensors is relatively coarse, with pixel sizes typically greater than $300 \times 300 \text{ m}^2$. As a result, these global BA products are not suitable for studying fine-scale burned patterns or individual fire events. Still, they are useful for monitoring large-scale fire activity and estimating global BA at regional or global scales (Chuvieco et al. 2020). The MCD64A1 product, produced by NASA based on MODIS 500-m reflectance bands guided by active fires, is the most widely used global BA product (Giglio et al. 2018). The European Space Agency's (ESA) Climate Change Initiative (CCI) Fire Disturbance project has developed the FireCCI51 product, an alternative global BA product based on MODIS 250-m near-infrared band and active fire information from thermal channels that are capable of detecting smaller burn patches (Lizundia-Loiola et al. 2020; Chuvieco et al. 2020).

Additionally, EO has proven to be a useful tool for monitoring and tracking land cover and land use change (LCLUC; Hall et al. 1991; Bontemps et al. 2015; Lamarche et al. 2017; Harper et al. 2023). In recent decades, there have been numerous studies that have utilized RS to monitor and forecast fires, as well as investigate their effects on LC and climate at both global and regional levels (Giglio et al. 2018; Laurent et al. 2018; Andela et al. 2019, 2022). Furthermore, researchers have developed fire models that can be integrated into climate models to provide future predictions (Yue et al. 2014; Drüke et al. 2019; Joshi and Sukumar 2021).

In tropical and subtropical regions, most of the fire ecology studies have been concentrated on tropical savannas, wetlands, and rainforests (Jones et al. 2022), neglecting the study of other ecosystems, such as dry

tropical forests, which constitute over 40% of the global tropical forests (Olson et al. 2001) and face considerable deforestation and degradation due to fires (Kuemmerle et al. 2017; Siyum 2020; De Marzo et al. 2021). This biased preference is evident in South America, where most recent studies were either for the whole continent at a large scale (Drüke et al. 2019; Armenteras et al. 2021) or focused on the Brazilian Pantanal (Kumar et al. 2022; de Magalhães and Evangelista 2022), Caatinga and Cerrado (Hoffmann et al. 2012), and most importantly, on the Amazonian hotspot (Le Page et al. 2017; Brando et al. 2020; Andela et al. 2022).

The South American Chaco ecoregion, extending over Argentina, Paraguay, Bolivia, and Brazil (Bucher 1982; Olson et al. 2001), has not received much attention until recently (Argañaraz et al. 2015a, b, 2018; Kuemmerle et al. 2017; De Marzo et al. 2021, 2022, 2023). To the West, this region contains the second largest forest in South America after the Amazon, which is also the largest continuous dry tropical forest and one of the most important global reservoirs of native forests in the world, known as the Gran Chaco forest (Dry Chaco subregion; Torrella and Adámoli (2005)). To the East, a savanna-like gradient leads toward some of the most extensive fresh-water wetlands in the globe, known as the Esteros del Ibera (Wet Chaco subregion; Ginzburg et al. (2005)). The Gran Chaco dry forest has been identified as a deforestation hotspot due to agricultural expansion (Marinaro et al. 2017; Torrella et al. 2018; Arriaga Velasco-Aceves et al. 2021; de la Sancha et al. 2021; Baumann et al. 2022), replacing forests with pastures for grazing or commodity crops (mainly rainfed soybeans in areas with mean annual rainfall over 700 mm/year; Grau et al. 2005; Boletta et al. 2006; Gasparri and Baldi 2013).

The Chaco is a fire-exposed region with a long history of periodic fires (Kunst and Bravo 2003; Argañaraz et al. 2015a, b; Jaureguiberry et al. 2020; Bravo et al. 2021). Commonly, the fires start in managed or unmanaged grasslands, savannas, or croplands, eventually spreading into neighbor forests and shrublands with significant effects on biodiversity and ecosystem services (Bravo et al. 2010; Tálamo et al. 2013; Loto and Bravo 2020; Giorgis et al. 2021; De Marzo et al. 2022). Like other regions, some of these fires are natural or accidental, but most are anthropic and intentional, used for deforestation through slash-and-burn practices or as an agricultural management tool to clear vegetation or to promote crops and pastures (Gürtler 2009; Gasparri and Baldi 2013; Baumann et al. 2018; De Marzo et al. 2023).

Following the findings from the above-cited works held over the Chaco, the connections between anthropic fires and deforestation are explained by two practices: (1) fires are being used as a direct tool to deforest, with

unmanaged wildfires advancing over the forest, leaving a disturbed and cleared land behind; (2) forests are firstly cut with machines (such as bulldozers; Boletta et al. (2006)) to clear the area rapidly and fires are used to burn the accumulated biomass. Although the final result could be similar, the timing between fires and deforestation detections through RS differs. In the first case, fire detections precede the land cover change (LCC) with a short time lag between both, while in the second case, we should first detect the LCC and then the fire, and this lag time could vary from one area to another.

Regarding the connection between fires and climate variables, fires in Chaco have shown a direct relationship with rainfall. Precipitation has a significant influence on fire spread in the Chaco, but the precise nature of this interaction is not fully understood. In some regions, precipitation shows negative correlations with fires, with increased precipitation increasing fuel moisture levels, reducing fire spread, and conversely, decreased precipitation leading to increased fire spread (Argañaraz et al. 2015a, b, 2018; De Marzo et al. 2021). In contrast, in arid and semi-arid shrublands or savannas, higher precipitation can lead to above-normal vegetation growth and increased fuel load, increasing the risk of fire spread and frequency (Bravo et al. 2010).

While high-resolution LC maps are being developed to characterize LCLUC in Chaco (Mapbiomas Chaco n.d; Baumann et al. 2022), the use of RS to quantify and understand the effects and drivers of fires over particular LC in this region as a whole is scarce (Argañaraz et al. 2015a, b, 2018; Landi et al. 2021; De Marzo et al. 2021, 2022, 2023). For the entire South American continent, Armenteras et al. (2021) used MODIS BA and LC products to investigate the links between fire frequency and forest loss over the 2001–2018 time period. They found that while the detrimental effects of one-time fires are big, forest loss becomes more pronounced as fire frequency increases. Notably, they show that approximately 48% of South America's evergreen forests that burnt between 2002 and 2003 underwent transformation and were lost by 2018 in the entire region.

Focusing on the Argentine Dry Chaco, De Marzo et al. (2021, 2022, 2023) used Landsat imagery to study the causes and consequences of forest disturbances between 1990 and 2017. They found that post-disturbance trajectories depend on the disturbance agent, and anthropic fires stand out as a major one with strong negative impacts on woody vegetation and its recovery. Still, further research is needed to better understand the drivers and effects of fires over the distinct regions within the Chaco.

The aim of this study is to improve the understanding of fire drivers in the Chaco and their interactions with LU and climate. More specifically, our objectives are to use RS products to:

- Characterize the frequency, seasonality, and distribution of fires in the South American Chaco between 2001 and 2019
- Identify connections to LCLUC, meteorological anomalies, and regional climate
- Assess potential links and lag time between fires and forest loss and degradation

Methods

Study region

Location and climatology

Our work is focused on the South American Chaco region (Fig. 1a). It encompasses 1,080,532 km², including two distinct areas: the Dry Chaco (80.9%—788,403 km²) covered by dry tropical forests and shrublands and the Wet Chaco (19.1%—292,128 km²) characterized by extensive floodplains, wetlands, and savannas (Soares 1990; Olson et al. 2001). This region shows a marked annual precipitation gradient from the East, showing up to 1800 mm/year, to the Southwest with less than 300 mm/year (2001–2019 average, Fig. 1b).

The Chaco is distributed between Argentina (60.4%—652,678 km²), Paraguay (28%—302,705 km²), Bolivia (11.5%—123,679 km²), and to a much less extent, Brazil (0.1%—1471 km²).

Forests and shrublands in the Dry Chaco show large fragmentation due to the expansion of agriculture (Cabrera 1976; Torrela et al. 2011; Adámoli et al. 2011). The Wet Chaco is mostly covered by grasslands and savannas, some of which are permanently or seasonally flooded, with natural or planted forest patches (Ginzburg et al. 2005).

The temperature seasonality exhibits a warm summer (DJF) and a cool winter (JJA) pattern, with mean maximum daily temperatures ranging from +15 to +40 °C and mean annual values of around +22 °C (both calculated for the period 2001–2019 with the W5E5v2.0 product described in the section “Data”; Fig. 1c, d).

Regarding precipitation, this area is characterized by a winter dry season from May to September (mean monthly minimum of 8.6 mm and 35.7 mm for the Dry and Wet Chaco, respectively, both happening in August and a summer wetter season from October to April (mean monthly maximum of 133.2 mm in January for the Dry Chaco and 181.2 mm in November for the Wet Chaco; all values are calculated over the period 2001–2019 with the W5E5v2.0 product described in the section “Data”).

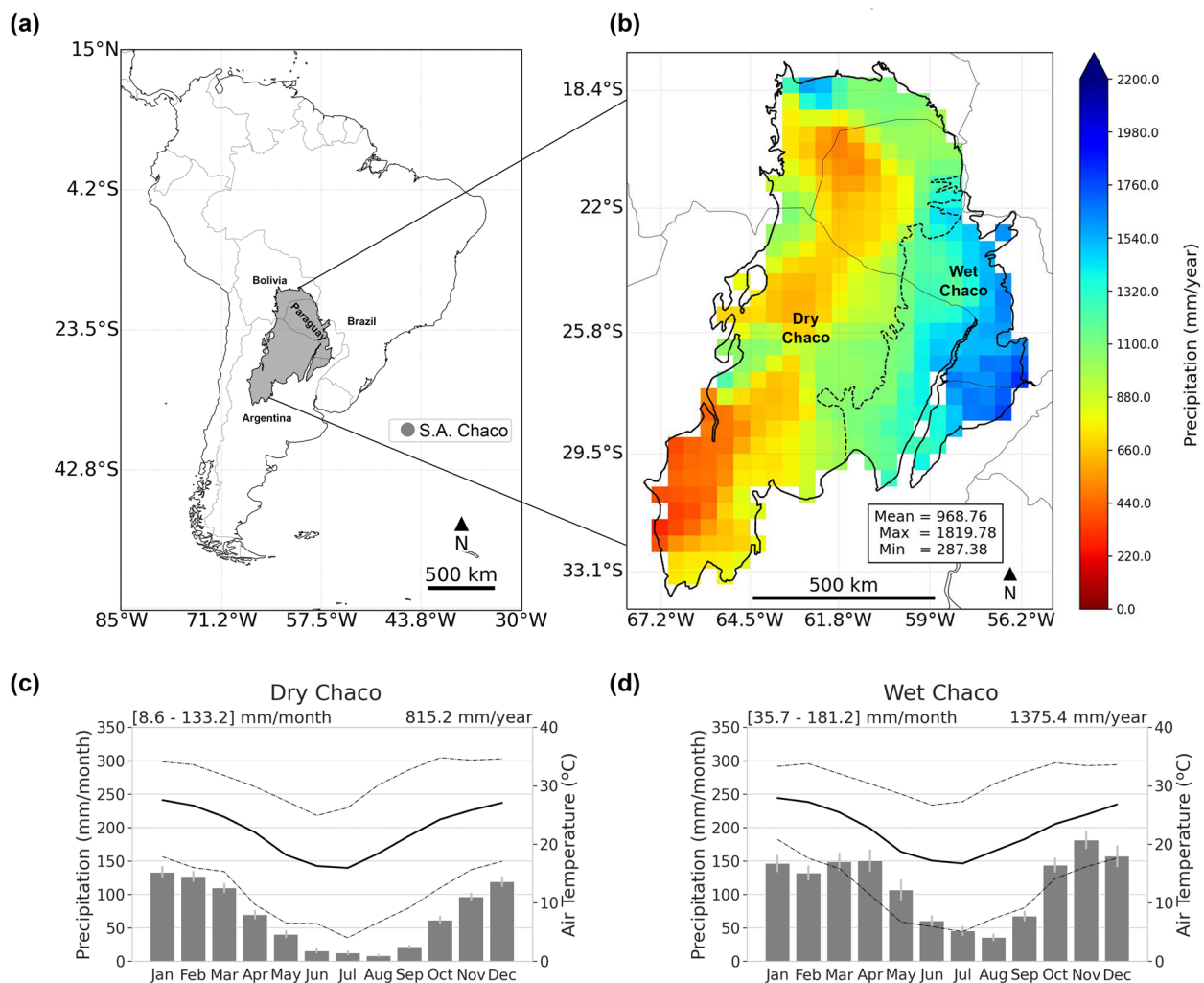


Fig. 1 **a** South American Chaco region (Olson et al. 2001). **b** Mean annual precipitation for 2001–2019 in mm/year with the delimitation of the Dry and Wet Chaco subregions. **c, d** Annual cycles of temperature and precipitation for the Dry (**c**) and Wet (**d**) Chaco for the period 2001–2019. Annual cycles present the monthly average values. Monthly minimum and maximum averaged precipitation are shown in the upper left corner and mean annual precipitation is shown in the upper right corner. The dotted lines represent the maximum (top) and minimum (below) monthly averaged temperatures. Gray lines over the bars represent the standard error of the monthly means. Temperature and precipitation values are calculated from the W5E5v2.0 product at 0.5° resolution

Data

EO products

Land cover The CCI Medium Resolution Land Cover (MRLC) product (called LandCoverCCI in this study) provides LC maps at a resolution of 10 arc secs (~ 300 m), covering the entire world (Defourny et al. 2023; Harper et al. 2023). The maps are generated annually from 1992 to 2020 and are based on a classification system developed by the United Nations Food and Agriculture Organization (UNFAO). This system consists of 22 primary LC classes and 15 sub-classes, defined by various combinations of fundamental landscape elements known

as “classifiers.” Every 300-m pixel is assigned a single LC class each year, with a change detection algorithm monitoring 13 possible LC transitions over time. The algorithm requires two consecutive years of consistent classification to register a change in LC class. However, a lack of change in a pixel’s assigned class does not necessarily indicate an absence of change in the land surface.

The maps and associated quality flags are publicly available in GeoTiff format at <https://maps.elie.ucl.ac.be/CCI/viewer/> (last access on 18 April 2023) and NetCDF format at <https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-land-cover> (last access on 18 April 2023).

Fires The ESA CCI Fire v5.1 product (FireCCI51), based on MODIS 250-m near-infrared band and active fire information from thermal channels, includes three dataset layers: date of BA detection (0 for no detection and 1–365 for the day of the year of detection), confidence level (probability that the classification of the BA is correct), and “land cover” (Chuvieco et al. 2018). The product is provided in two formats: the “FireCCI51 pixel product” has a resolution of 0.00224573° (~ 250 m) with either a sinusoidal or a geographic lat/lon projection, and the “FireCCI51 grid product” which summarizes the pixel information to a regular grid of 0.5° in geographic lat/lon projection.

For the LC classification, the algorithm used the LandCoverCCI product presented above to generate a burnable mask, chosen among other global products for program consistency and temporal and spatial resolution similarities. The burnable mask of each year was obtained by removing urban areas, bare areas, water bodies, and permanent snow and ice classes (Lizundia-Loiola et al. 2020). Given that only the LC for burnt pixels is given, in our study, we combined this information with the original LandCoverCCI product to obtain both the burnt and unburnt LC.

Fires are not limited to one fire per year as some regions can burn in the beginning and at the end of the same year. To avoid double counting of fires that start at the end of 1 month and continue into the next, a 2-month filter was applied to avoid having fire detections in consecutive months.

The product is available in NetCDF format for the period 2001–2019 at <https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-fire-burned-area> (last access on 18 April 2023) and in GeoTiff format for the period 2001–2020 at <https://catalogue.ceda.ac.uk/uuid/58f00d8814064b79a0c49662ad3af537> (last access on 18 April 2023).

Atmospheric data

The climatology of the region was assessed using the W5E5v2.0 atmospheric reanalysis product (Lange 2019). This product is derived from the WFDE5 dataset (Cucchi et al. 2020), which covers land and ocean, and was generated using the Water and Global Change (WATCH) Forcing Data (WFD) methodology applied to bias correct surface meteorological variables from the ERA5 reanalysis (Hersbach et al. 2020). The WFD correction methodology used gridded observations of monthly average air temperature, diurnal temperature range, cloud cover (for adjusting average downward shortwave fluxes), total precipitation, and the number of “wet” days (i.e., precipitation days) from the Climatic Research Unit (CRU)

dataset. It has been resampled at 0.5° and daily temporal resolution (from the original hourly and 0.25° resolutions of WFDE5). The product is available from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) repository for the period 1979–2019. The data is available in NetCDF format at <https://data.isimip.org/10.48364/ISIMIP.342217> (last access on 18 April 2023).

For this study, we extracted the daily precipitation, max/mean/min air temperature, humidity, and wind speed and calculated the atmospheric vapor-pressure deficit (VPD) to examine the links between fires and climate.

Data processing and analysis

Land cover data processing

To study the LC transitions related to BA, we reclassified the original 22 categories (Harper et al. 2023) into eight general groups: (1) tree cover (including all tree cover classes, flooded or not—classes 50, 60, 61, 62, 70, 71, 72, 80, 81, 82, 90, 160 and 170); (2) grasslands (class 130); (3) croplands (classes 10, 11, 12 and 20); (4) mosaic of croplands and natural vegetation (classes 30 and 40); (5) mosaic of trees, herbs and shrubs (classes 100 and 110); (6) flooded vegetation, including only shrubs and herbaceous cover (classes 180); (7) shrublands (class 120), and (8) others, including bare areas, sparse vegetation, urban areas, and water bodies (classes 150, 151, 152, 153, 190, 200, 201, 202, 210).

Fire data processing

For our study, we used the FireCCI51 pixel product (see the section “Data”). After confirming that 94% of pixels have a confidence level above 70%, we decided to keep all the pixels classified as burnt. We transformed the product using the day of fire detection at each monthly time step to generate a daily time step dataset with binary information of fire detection (1) or not (0). This allowed us to look at fire detections more easily and produce statistics that could be compared to daily climate variables.

As described in the FireCCI51 Product User Guide (Pettinari, Lizundia-Loiola, and Chuvieco 2020), the FireCCI51 pixel product contains some artefacts produced in the re-projection from MODIS sinusoidal to the latitude–longitude grid, with pixels escaping the 2-month filter set to avoid fires in consecutive months. To fix this, we applied a new filter to add a minimum gap of 2 months between one fire and the next.

Using the area of each pixel, we calculated the total BA at a daily time step, which could then be aggregated into monthly or annual totals. We used the monthly and annual averages for 2001–2019 as a base to calculate monthly and annual anomalies. BA and BA anomalies were calculated for different regions (full Chaco, Dry

Chaco, Wet Chaco, and over different precipitation bins using meteorological data), aggregating the area of each 250 m pixel within them.

Atmospheric data processing

The analysis of the links between precipitation and BA was done using the 0.5° grid of the W5E5v2.0 product. We calculated the annual mean precipitation for each pixel and then classified these pixels in precipitation bins. For each pixel, we calculated different combinations of monthly accumulated precipitation to compare them to monthly BA anomalies. We computed Pearson linear correlations between precipitation and BA anomalies for all the 0.5° grid cells included in the different classes of annual precipitation amount previously defined.

Mean and maximum air temperatures, VPD, and wind speed were used similarly within each 0.5° pixel at daily, 15-day, and monthly time scales to calculate the linear regressions with the BA anomalies within the pixel.

Forest loss and forest gain

In this work, forest loss is defined as the conversion of the tree cover to any other LC type, and conversely, forest gain is defined as the conversion of any LC type to tree cover. For most of our analysis, we considered 2001 forest cover as a base, and we calculated the forest loss as the fraction converted to other types by 2019. We used forest loss and deforestation as synonyms.

Forest loss and fires

To better understand the sequence of events and the magnitude of the temporal gap between forest loss and fire occurrence, we analyzed the average time interval between forest loss and fire detection in pixels that exhibited a single fire detection event between 2001 and 2019. To achieve this, we restricted our analysis to pixels that had forest cover in 2001 and underwent LCC leading to non-forest vegetation by 2019. Specifically, we identified pixels that experienced fire events each year and calculated the proportion of these pixels that transitioned from forest cover to non-forest vegetation before and after the year of the fire. For pixels that had already undergone forest loss before the fire, we estimated the retrospective time interval between forest loss and fire occurrence. Conversely, for pixels that retained forest cover by the year of the fire, we prospectively calculated the year-lag between the fire event and forest loss.

Fires and climate

To study the links between fires and climate, we separated each 0.5° pixel of the W5E5v2.0 product according to their mean annual rainfall between 2001 and 2019

and we compared anomalies of BA and climate variables within each pixel.

BA anomalies were calculated at daily and monthly time steps for each time series from the differences between interannual averages over the whole period, using as total monthly BA the surface of all the burnt FireCCI51 250-m pixels within each 0.5° pixel of the W5E5v2.0 product. The assessment of the relationships between BA and meteorological variables anomalies was finally analyzed at monthly time steps to limit errors in the daily time steps related to the uncertainties in the exact date of the fire event (Lizundia-Loiola et al. 2020).

Two different approaches were followed for the different climate variables. For temperature, wind speed, and VPD, correlations were computed at monthly scale. For rainfall, given the soil buffering effect and the delay in the response of vegetation to hydric stress, we first search for the time period for which preceding precipitation has the larger impact on fire activity, i.e., for which precipitation anomaly is the best correlated to the BA anomalies. We tested different time periods ranging from 1 to 12 months of accumulated rain and found that larger temporal correlations were obtained for a 3-month accumulation period. This was finally retained to calculate antecedent rainfall as a proxy for soil hydric state.

Results

Land cover analysis

Figure 2a presents a detailed LC map generated from the LandCoverCCI product for 2019, showcasing the diverse landscapes within the South American Chaco region, including both the Dry and Wet Chaco areas (788,403.39 km² and 292,128.78 km², respectively). The map's legend depicts the 20 distinct LC classes which are present in the study region. The classes were grouped into 8 major classes following the protocol described in the section “Methods”.

The Dry Chaco predominantly comprises woody vegetation (over 75%), mostly composed of broadleaved deciduous and evergreen trees and shrubs (37.3% and 38.2%, respectively; Fig. 2c).

Conversely, the Wet Chaco region presents a heterogeneous natural and modified landscape dominated by herbaceous vegetation distributed in grasslands, wetlands, croplands, and mosaics of them (47.5% altogether), with woody vegetation dispersed among them (41.5%). Both regions contain a similar fraction of croplands (~10%).

Fire characterization

Fire frequency

Based on the FireCCI51 product, Fig. 2b provides a visual representation of the fire activity that occurred in the Dry and Wet Chaco between 2001 and 2019. The

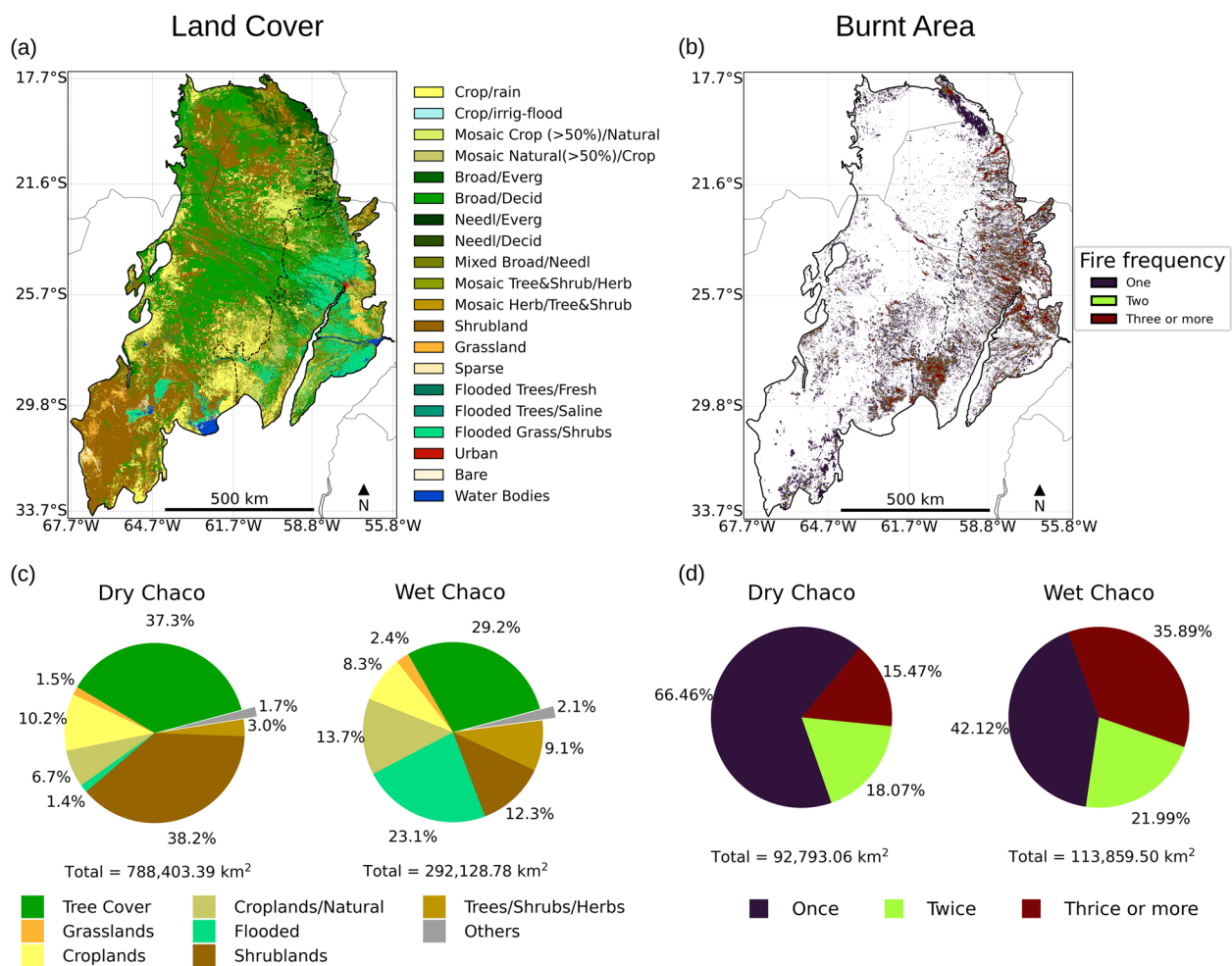


Fig. 2 **a, c** LandCoverCCI map for 2019 over the South American Chaco and pie charts showing the major classes distribution present in the Dry and Wet Chaco after regrouping LC classes. **b, d** FireCCI51 map showing the total number of fire detections between 2001 and 2019 over the Chaco and pie charts with the fraction of fire detections over the burnt pixels for the Dry and Wet Chaco, grouped into three categories (burnt one, two, and three or more times)

total number of fires detected per pixel over the whole study period (2001–2019), ranging from 0 up to 22, are grouped into 3 classes (one, two, and three or more fire detections). Table 1 summarizes the corresponding surfaces of such BA.

The data analysis highlights a significant discrepancy between the fire patterns observed in the two regions. The Wet Chaco exhibited a larger BA with a total of 113,859 km² of surface burnt at least once during the 20-year period, compared to the 92,793 km² burnt in the Dry Chaco. These areas represent 39% and 12% of their respective total extent (Fig. 2d). Furthermore, the Wet Chaco experienced a higher incidence and frequency of repeated fires on burnt pixels than the Dry Chaco, with 42.12%, 21.99%, and 35.89% of pixels exhibiting one, two, and three or more fire detections, respectively.

In contrast, the Dry Chaco showed more sporadic fire detections and fewer instances of consecutive fire outbreaks (66.46%, 18.07%, and 15.47% of pixels with one, two, and three or more fire detections respectively). The Wet Chaco also exhibited specific regions that stood out as hot spots of fire activity, with certain isolated pixels experiencing more than 20 fire detections over the 20-year study period. Most of these fires were detected over flooded vegetation, which presented the highest frequency of fires among all other LC types (see Supplementary Figure S1).

Fire seasonality

Figure 3 presents the fire activity seasonality in the Dry and Wet Chaco regions in boxplots. The boxes display the mean, minimum, maximum, second, and third

Table 1 Area in km² of the studied regions and the different pixel selections used according to their fire detection frequency

Area ¹	Dry Chaco	Wet Chaco	Full Region
Burnt once	61,673 km ² (7.8%/66.5%)	47,963 km ² (16.4%/42.1%)	109,636 km ² (10.1%/53.1%)
Burnt twice	16,769 km ² (2.1%/18.1%)	25,032 km ² (8.6%/22%)	41,801 km ² (3.9%/20.2%)
Burnt thrice or more	14,352 km ² (1.8%/15.5%)	40,864 km ² (14%/35.9%)	55,216 km ² (5.1%/26.7%)
Total burnt	92,793 km ² (11.8%)	113,860 km ² (39%)	206,653 km ² (19.1%)
Unburnt	695,610 km ² (88.2%)	178,269 km ² (61%)	873,879 km ² (80.9%)
Total area	788,403 km² (80.9%)	292,128 km² (19.1%)	1,080,532 km²

¹ Pixels selected using the frequency of fire detections from the FireCCI51 product for the period 2001–2019. The total number of fires detected per pixel was grouped into 3 classes (burnt once, burnt twice, and burnt thrice or more). For the first three rows, the percentages represent the area of each class within the Total area of each subregion (left) and the area of each class among the Total BA only (right). For the Total burnt and Unburnt rows, the percentages are based on the Total area of each subregion, while those of the Total area row are calculated from the Total area of the Full region column

quartiles of the distribution of the total monthly BA in km², calculated over 2001–2019. The box plots show that the Wet Chaco region has more fires (larger BA) and two fire seasons (bimodal seasonality): an intense fire season with a significant number of fires in the late winter to early spring (dry season) and a mild one in the late summer to early autumn (wet season). On the other hand, the Dry Chaco region presents a single fire season (unimodal seasonality) in the late winter to early spring (dry season).

The interannual variability as assessed by the interquartile range (distance between the upper and lower quartiles) appears to be larger in the Wet Chaco compared to the Dry Chaco, suggesting a higher sensibility to external factors in the fire ignition and spread.

To better analyze the reasons for these differences, we further analyzed the links between fires, vegetation type, and meteorological conditions to assess the BA sensitivity to these potential environmental drivers.

Links between fires and land cover

Figure 4 shows the annual BA for the Dry and Wet Chaco during the 2001–2019 period. As shown in Fig. 2, the Wet Chaco has a consistently higher annual BA than the Dry Chaco (except for the year 2019) despite having a smaller total surface area. The fraction of burnt land during this period in the Wet Chaco is considerably larger than that of the Dry Chaco (39% and 11.8%, respectively; Table 1), indicating that the Wet Chaco is more vulnerable to wildfires than the Dry Chaco.

Although the BA in both subregions slightly declined over time, the Dry Chaco experienced an exceptionally high BA in 2019, with a more significant proportion of burnt tree cover compared to previous years. Besides, both regions showed a minimum BA in 2014 and 2015.

Regarding the burnt LC, Fig. 4 displays that both subregions exhibit a similar proportion of burnt tree cover, normally varying between 20 and 30% per year. Exceptionally, in 2019 the burnt tree cover rate rose to 37% in

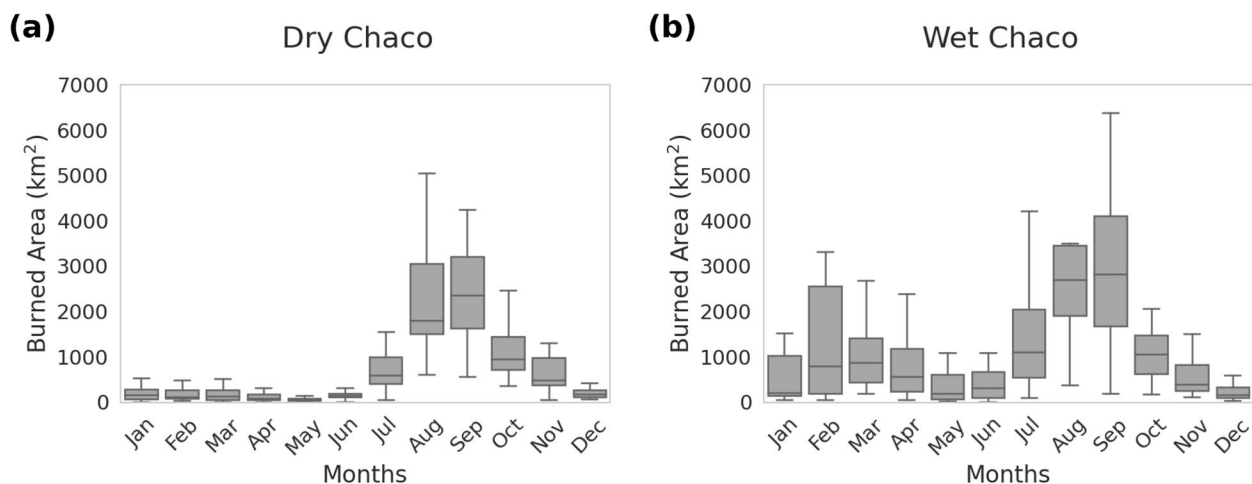


Fig. 3 Boxplots of the seasonality of fire activity (represented as burnt area in km²) in the Dry (a) and Wet (b) Chaco. The data used to create the plots represents the average monthly burnt area values calculated over 2001–2019

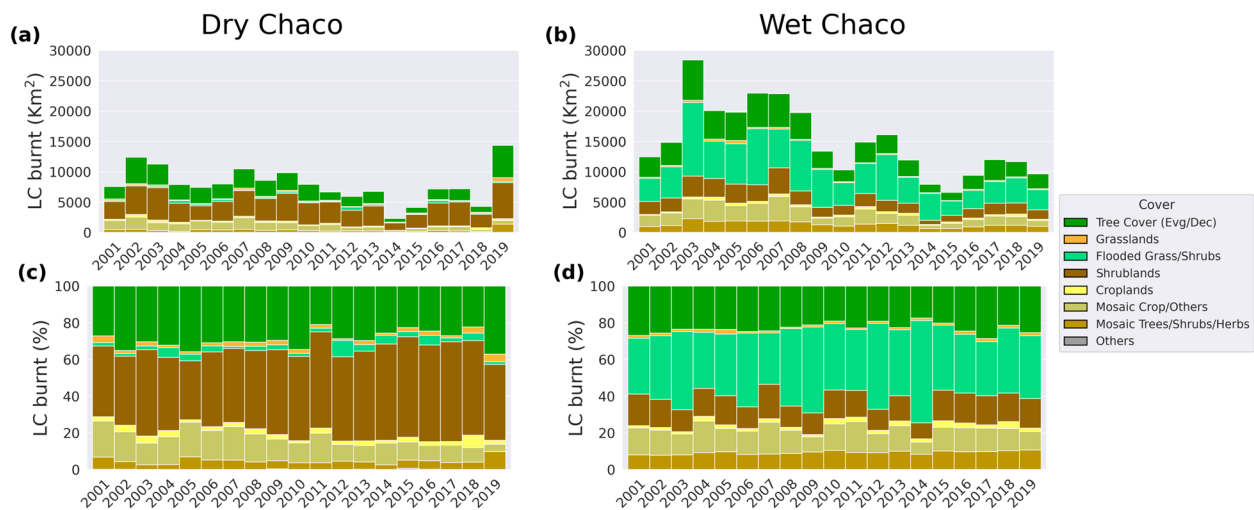


Fig. 4 Bar plots showing total and proportional annual burnt area divided into land cover classes for the Dry (a, c) and Wet (b, d) Chaco between 2001 and 2019. Area is expressed in km², and all the data was retrieved from the FireCCI51 product

the Dry Chaco. In general, the Dry Chaco has a higher percentage of annually burnt shrublands than the Wet Chaco (45.5% in average in the Dry Chaco against 14.2% in the Wet Chaco), while the latter shows a higher occurrence of regularly burnt flooded vegetation (3.2% in average in the Dry Chaco against 37.2% in the Wet Chaco).

In order to understand the links between fires and LC, Fig. 5 shows the annual percentages of the LC classes found over the Dry and Wet Chaco, respectively, separating the pixels without fire detections between 2001 and 2019 (upper panel) from those with at least one fire detection (lower panel). We can learn from these bar plots that the connection between forest loss and fire detection is significantly stronger over the Dry Chaco. Both regions had a similar ratio of fire detections over

tree cover, but the Wet Chaco showed a smaller relative forest loss than the Dry Chaco between 2001 and 2019 (13% against 24%). Over the Dry Chaco, we can also distinguish a larger ratio of unburnt deforestation (77.6% of its total deforestation) than in the Wet Chaco (48.5% of its total deforestation).

The distribution of this forest loss can be seen in Fig. 6, which presents the forest loss and forest gain (defined in the section “[Methods](#)”) with and without fire detections. These plots highlight that most deforestation is detected over unburnt pixels (74%) and that spatial differences between the countries of the Chaco are clearly visible.

These features led us to further analyze our results at the country level (Table 2). Argentina experienced the largest deforestation with 51,409 km² of its Chaco

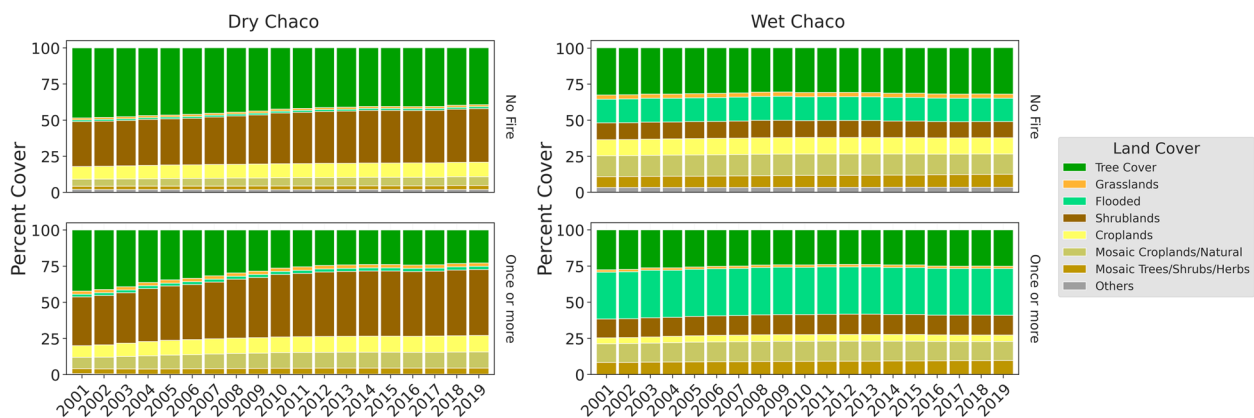


Fig. 5 Bar plots showing the proportions of land cover classes annually over the Dry (left panel) and Wet (right panel) Chaco for pixels without fire detections (top) and with at least one fire detection (below) between 2001 and 2019. Land cover data was retrieved from the LandCoverCCI product at 300 m and the fire detections were retrieved from the FireCCI51 product rescaled to 300 m

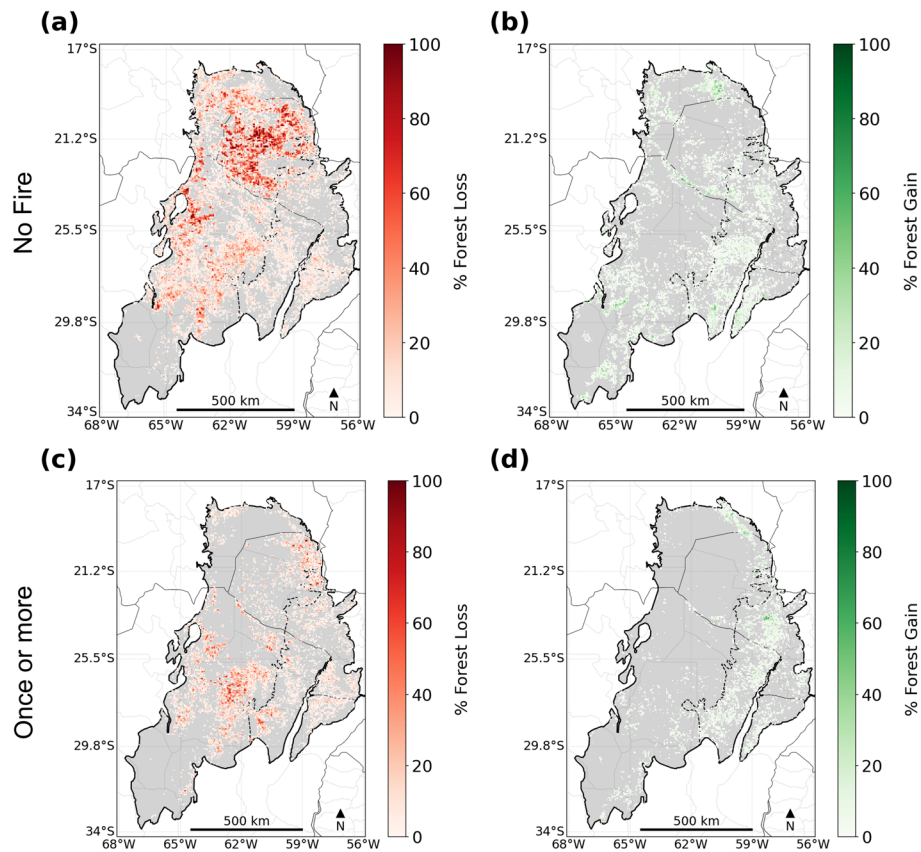


Fig. 6 Forest loss and gain maps for pixels without fire (**a, b**) and with one or more fires (**c, d**) between 2001 and 2019. Data retrieved from the LandCoverCCI and the FireCCI51 products and rescaled to a 0.05° spatial resolution

Table 2 Area in km² of forest loss at the country level

Forest loss ¹	Argentina	Paraguay	Bolivia	Brazil
Burnt	19,720 km ² (38.4%)	7005 km ² (15.3%)	688.6 km ² (7.9%)	30.6 km ² (65%)
Unburnt	31,688 km ² (61.6%)	38,747 km ² (84.7%)	8042 km ² (92.1%)	16.5 km ² (35%)
Total	51,409 km ² (20.7%)	45,752 km ² (28.6%)	8731 km ² (12.2%)	47 km ² (10.6%)

¹ Areas of forest loss are calculated as the surface of tree cover in 2001 that is transformed to any other LC type by 2019 using the classification of the LandCoverCCI product. Fire detections between 2001 and 2019 come from the FireCCI51 product. Percentages of the Burnt and Unburnt rows show the relative burnt or unburnt forest loss based on the Total Chaco forest loss surface within each country between 2001 and 2019. Percentages of the Total row show the fraction of forest loss by 2019 relative to each country's total Chaco forests by 2001

forests lost from 2001 to 2019, representing 20.7% of its Chaco forest cover by 2001. Paraguay, on the other hand, showed a lower deforested area, with 45,752 km² of its Chaco forest lost over the same time frame, but this represented a larger fraction of its total Chaco forest cover by 2001 (28.6%). During the same period, Bolivia experienced a comparatively lower forest loss with 8731 km² of its Chaco forest lost, representing 12.2% of its Chaco tree cover by 2001 whereas Brazil lost 47 km² of its Chaco forests, representing 10.6% of its 2001 Chaco forests.

Another difference in the fire patterns of each country is the connection between the mentioned forest loss and fire detections. Argentina showed the highest percentage of forest loss related to fires, with 38.4% of its deforestation occurring over BA from 2001 to 2019. In contrast, Bolivia and Paraguay experienced a lower fraction of fire detections over deforested pixels, with only 7.87% of Bolivia's deforestation and 15.3% of Paraguay's deforestation occurring over BA from 2001 to 2019. Although Brazil's Chaco surface is negligible compared to that of the other countries, 65% of its Chaco deforestation occurred over BA.

Looking at the forest gain ratios maps shown in Fig. 6c, d, we see that forest regeneration or reforestation is not abundant in any of the regions studied. For both the Dry and the Wet Chaco, we have larger forest gains over pixels without fire detections. When we look at burnt pixels, we can see that most of the forest gain occurs over the Wet Chaco.

Figure 7 summarizes our analyses of the connection between forest loss and fire events in the Chaco region. Following the methodology described in the section “Methods,” we represented the averaged year lag between forest loss and fire detections in the two subregions. The plot clearly highlights that forest loss often precedes fires. The results are more conclusive for the Dry Chaco, where we found that more than 50% of forest loss occurs between the 3 years before and the first year after the fire detection. It should be noted that forest loss occurring in the same year as a fire could be marked as either -1 or $+1$, which could lead to a bias in those two bars. However, despite this potential bias, the overall trend of significant forest loss preceding fires is still apparent in our results.

Links between fires and climate

The analysis of the time series anomalies of BA, precipitation, and air temperature at an annual scale shows that the years with minimum fires (i.e., 2014 and 2015) corresponded to the years with maximum precipitation (Supplementary Figure S2). Minimum and mean temperatures were also at their highest during these years. At the monthly scale, significant correlations were found with antecedent rainfall calculated over the 3-month period preceding the fire (see methodology the section

“Methods”). Our results are summarized in Fig. 8, which presents the Pearson correlation coefficients obtained between BA and 3-month antecedent rainfall according to annual rainfall amount and LC type. We divided the analysis into summer (top panel: February and March) and winter (mid panel: August and September) fire seasons.

The results show that for both the Dry and Wet Chaco, there were higher correlations between the monthly BA and the 3-month cumulative precipitation anomalies, especially in the wet areas and during summer. As we move across the precipitation gradient (Fig. 1), from West (dry) to East (wet), we begin to find more significant negative correlations.

We also detected significant positive correlations between rainfall and winter fires in areas below 1200 mm mean annual precipitation, and especially below 700 mm/year. As we can learn from the dominant LC at each pixel with p -values below 0.05, the positive correlations majorly occurred in pixels dominated by shrublands and the negative correlations in pixels mainly covered by flooded herbaceous vegetation.

Based on the same methodology, we extend our analysis to other meteorological variables such as maximum air temperature and VPD. Figure 9 presents the results obtained from the regressions between BA anomalies and 1-month averaged Tmax and VPD anomalies (negative VPD represents drier conditions). It shows, as expected, that the correlations are generally positive for Tmax and negative for VPD whatever the type of vegetation affected by fire, highlighting the positive impact of dry and hot conditions on fire activity. In winter, the air temperature seems to show less impact, but some pixels

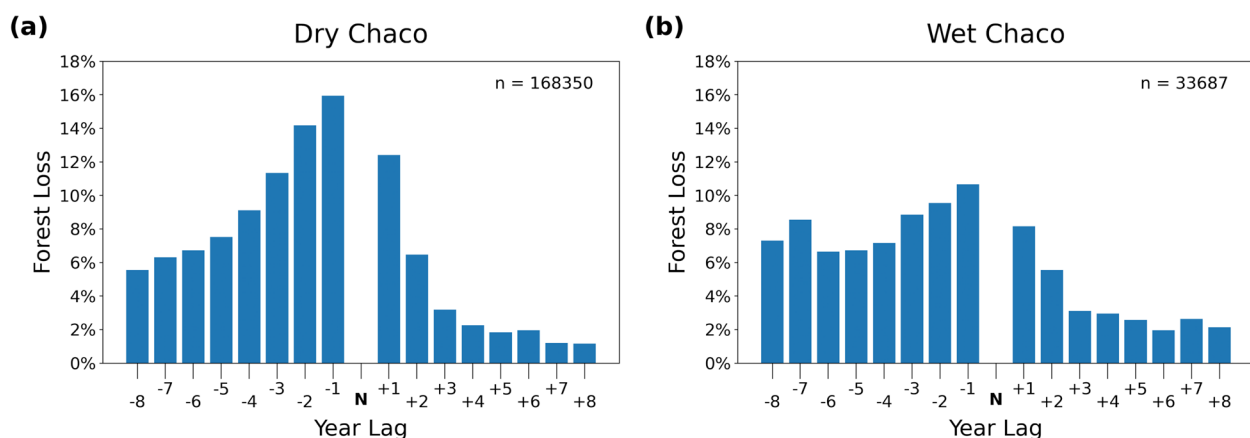


Fig. 7 Histogram connecting forest loss and fires in the Dry (a) and Wet (b) Chaco, showing the forest loss fraction and the year lag between the forest loss and the fire detections over each pixel. For a pre-selection of pixels that burnt only once through the period 2001–2019 and that were forest in 2001 and something else by 2019, we calculated the time distance between the year of the fire detection (N) and the moment of the forest loss (negative when the deforestation precedes fires, and positive when deforestation occurs after the fire). Land cover data was retrieved from the LandCoverCCI product at 300 m and the fire detections were retrieved from the FireCCI51 product rescaled to 300 m

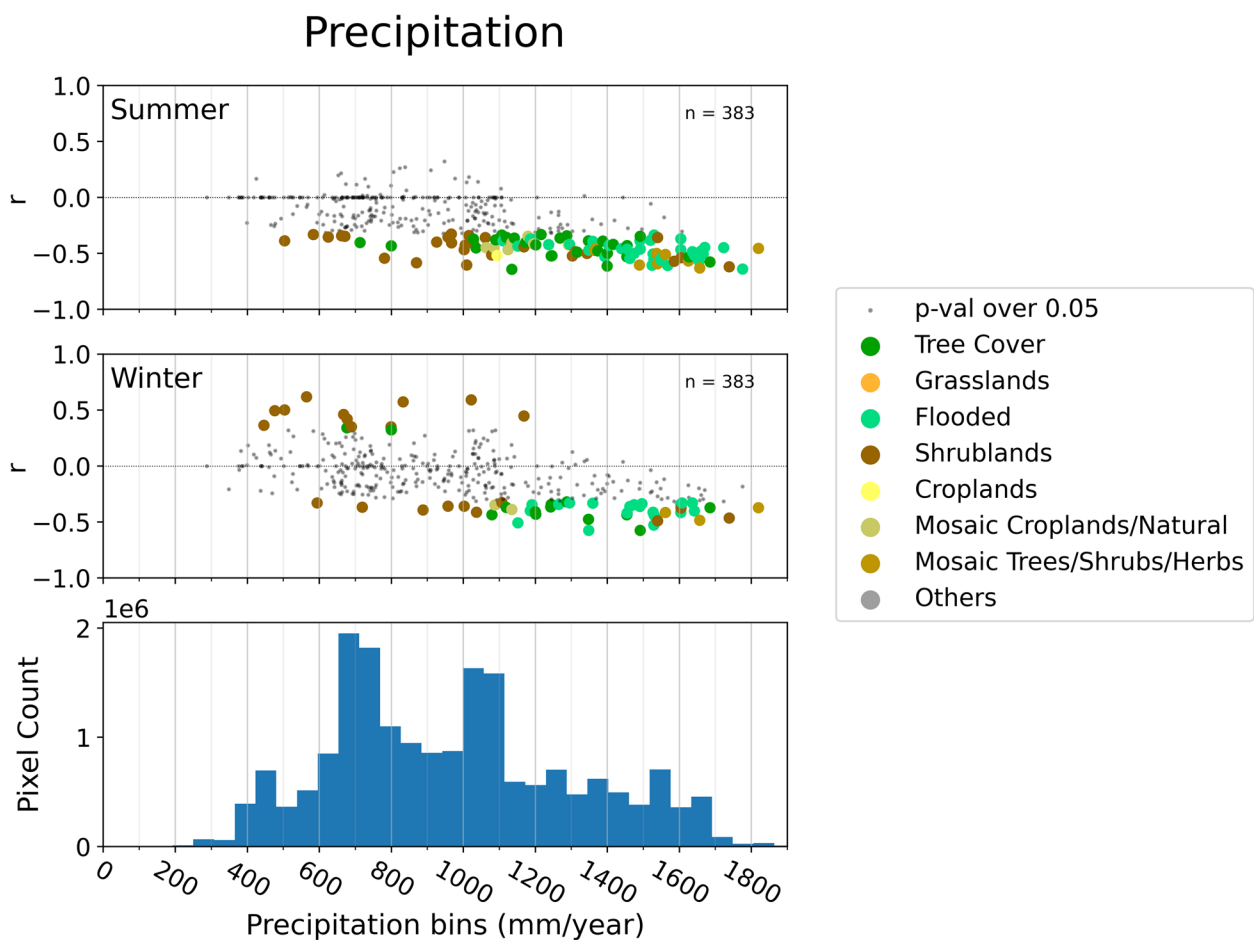


Fig. 8 Pearson correlation coefficients (r) of linear regressions of monthly total burnt area anomalies and 3-month accumulated precipitation anomalies. The top panel shows the results of summer correlations, using only values from February and March. The mid panel shows the results of the winter correlations, using only values from August and September. The bottom panel contains the precipitation histogram of the 0.5° resolution W5E5v2.0 product combined for the Wet and Dry Chaco, displaying the number of 250-m pixels from the FireCCI51 product that were found within each precipitation bin. A linear regression was calculated for each 0.5° pixel (383 pixels), which represented a unique mean annual precipitation bin, and each point in the correlation plots show the correlation coefficient (r) of the regression at each one of these 383 pixels. Values with p -value over or equal to 0.05 are shown in black. Values with p -value below 0.05 are shown with the color of the pixel's dominant land cover by 2019. The monthly burnt area anomalies were calculated using the 2001–2019 average monthly burnt area as the baseline. The 3-month accumulated precipitation anomalies were calculated at each month, using the 2001–2019 average 3-month accumulated rain for each month as the baseline

in dry areas present negative correlations between fires and Tmax anomalies and some show positive correlations between fires and VPD anomalies, suggesting that over these dry areas more fires can develop under cooler and more humid conditions.

Discussion

Compared to tropical rainforests, tropical and subtropical dry forests as the Chaco have been much less studied, but they are recently receiving more attention as important reservoirs of native forests and carbon stocks (Kuemerle et al. 2017; De Marzo et al. 2022). The severe fires that affected the Chaco in 2020 represented a wake-up call for

the scientific community to encourage and develop research on the environmental situation of this important region (Bonfanti and Sánchez 2021; Naval Fernández et al. 2023).

In this work, we intended to bring light to the fire regimes in the South American Chaco as a whole, comparing the particularities of the Dry and Wet Chaco sub-regions, in order to discuss potential drivers associated with LU and climate.

Role of land cover and meteorological conditions

Between 2001 and 2019, the Wet Chaco experienced a higher frequency of fires compared to the Dry Chaco. Certain regions within the Wet Chaco exhibited

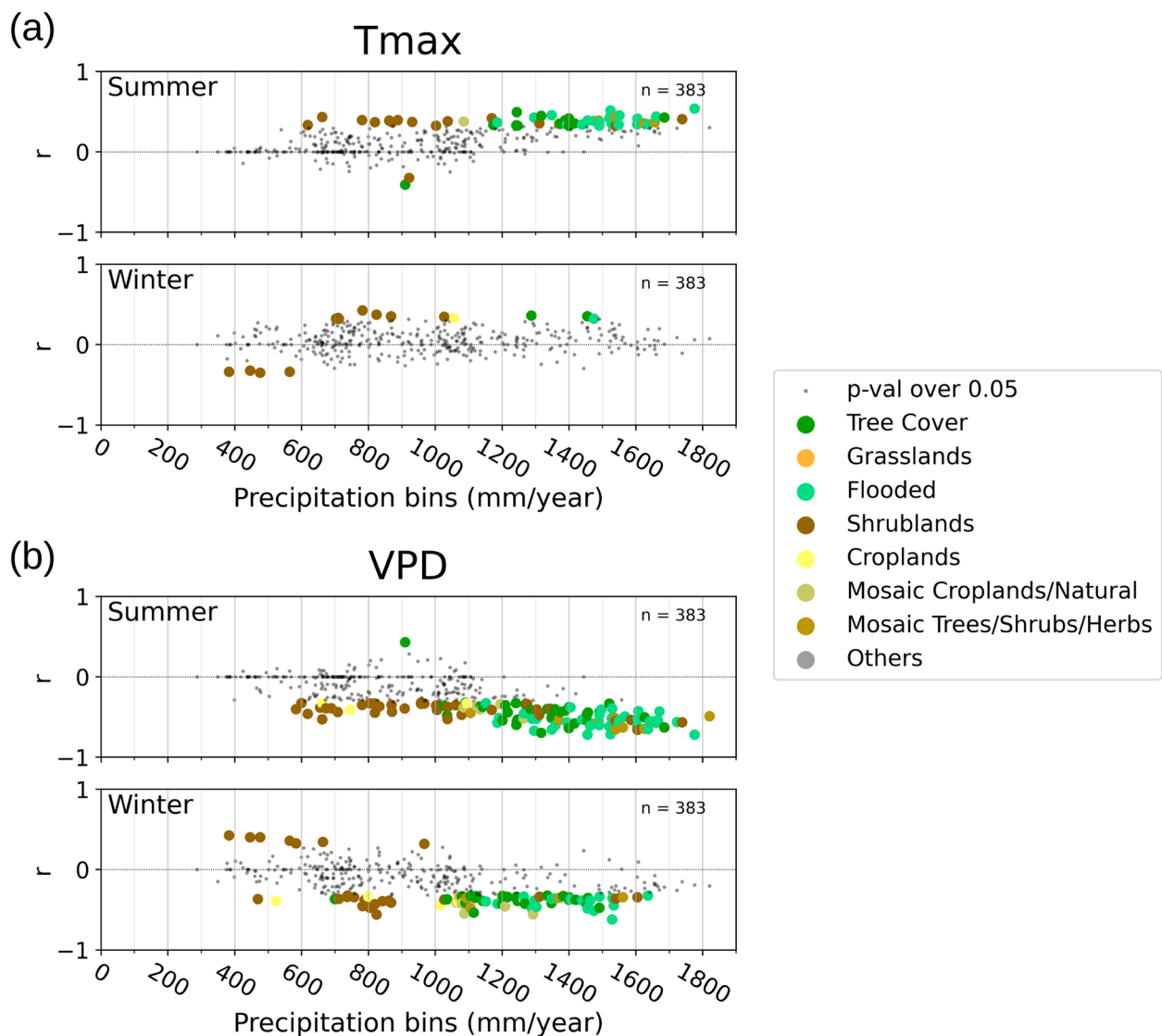


Fig. 9 Pearson correlation coefficients (r) of linear regressions of monthly total burnt area anomalies against **a** monthly maximum temperature anomalies and **b** and monthly VPD anomalies. For each correlation plot the top panel shows the results of summer correlations, using only values from February and March and the lower panel shows the results of the winter correlations, using only values from August and September. A linear regression was calculated for each 0.5° pixel (383 pixels) of the W5E5v2.0 product, which represented a unique mean annual precipitation bin, and each point in the correlation plots shows the correlation coefficient (r ; y-axis) of the regression at each one of these 383 pixels vs. the mean annual precipitation of the pixel (x-axis). Values with p -value over or equal to 0.05 are shown in black. Values with p -value below 0.05 are shown with the color of the pixel's dominant land cover by 2019. The monthly burnt area anomalies were calculated using the 2001–2019 average monthly burnt area as the baseline. The monthly mean Tmax and VPD anomalies were calculated using the 2001–2019 average for each month as the baseline

persistent and repetitive fire activity, while the Dry Chaco had fewer instances of consecutive fire outbreaks over a same area. The Wet Chaco had a larger absolute BA of 113,806 km², compared to the Dry Chaco's 92,793 km², which represents about 39% of the region's total area, compared to the Dry Chaco's 11.8%. This may be explained by the more fire-prone characteristics of the herbaceous vegetation in the Wet Chaco (highly

flammable grasses), such as savannas, grasslands, and flooded vegetation, as well as the higher productivity and faster regeneration of these plants, while the Dry Chaco contains xerophytic vegetation with dense wood and leaves with thick cuticles that make them resistant to droughts and fires (Cabrera 1976; Ginzburg et al. 2005; Adámoli et al. 2011; Torrela et al. 2011; Argañaraz et al. 2015a, b).

Previous studies have shown that global warming could expand fire seasons (Jolly et al. 2015) and increase fire frequency, intensity, and extension (Hantson et al. 2017). Our results reveal no significant increase in fire frequency or in the duration of fire seasons in the Chaco region between 2001 and 2019, but during a period of 19 years, regional changes induced by climate change may well be masked by internal variability (Doblas-Reyes et al. 2021). For both subregions, the years with the minimum total BA coincide with the years with particularly high rainfall (2014 and 2015), revealing links between these anomalies that are further discussed below.

In the Dry Chaco, fire seasonality is unimodal, with a maximum peak of fires after winter, the coldest and driest season in this region. This seasonality pattern can be explained by the accumulation of dry and dead plant material with low fuel moisture content during the dry period, promoting the late winter and early spring fires, as described by Bravo et al. (2014, 2021). This would agree with the global fire-productivity relationship described by Pausas and Ribeiro (2013), and the productivity-aridity gradient described globally in Pausas and Bradstock (2007), implying that fires in low-productivity and arid regions such as the Dry Chaco are not sensitive to warming but to abnormal fuel production when the right conditions are given (abundant precipitation without extreme temperatures).

Our findings highlight the positive significant correlations between winter BA anomalies and 3-month accumulated precipitation anomalies in the drier areas, indicating that an above-average precipitation in arid regions could promote vegetation overgrowth, and thus, fuel field available to ignition. These results were mostly found over shrublands, where the above-average growth of seasonal herbaceous vegetation during wetter years could increase the flammable fuel load. This is further confirmed by the negative relationship we found between high temperatures and fires over those areas, revealing that the extremely high air temperatures usually measured over this region could limit productivity partly because of the larger water loss by evapotranspiration. Conversely, cooler temperatures combined with larger rainfall and lower VPD could have a positive synergy promoting vegetation growth and thus producing more fuel. Still, as discussed by Argañaraz et al. (2018), these are not the only factors controlling flammability, as heat content, chemical compositions and fuel arrangement also play an important role and were not considered in this study.

On the other hand, in the Wet Chaco, fire seasonality is bimodal, with a first maximum peak after summer (wet season) and a second maximum peak after winter (dry season). As occurs in other similar wetlands (Brando

et al. 2020; Magalhães Neto and Evangelista 2022), this feature may stem from the interaction between anomalous low rainfall and temperature patterns with vegetation growth, causing the drying of the vegetation and increasing its flammability. This region would be in the high-productivity end of the fire-productivity relationship (Pausas and Ribeiro 2013), and our research confirms that these wet areas are more sensitive to anomalous dry and warm periods during summer, when temperatures are elevated and rainfall is expected to be plentiful. Briefly, our results suggest that the wetter the region, the more sensitive it is to rainfall variability in terms of fire ignition and propagation.

Role of land management

There has been substantial deforestation in the Chaco forests since the 1980s, mostly remarkable in Paraguay during the studied period. Previous works show that woody vegetation in the Chaco was historically distributed in fairly homogeneous patches and is currently facing a large and expanding human-induced fragmentation (Arriaga Velasco-Aceves et al. 2021; de la Sancha et al. 2021). Forests are being replaced by agricultural lands such as croplands or grasslands for cattle grazing (Grau et al. 2005; Torrella et al. 2018; Arriaga Velasco-Aceves et al. 2021; de la Sancha et al. 2021; Baumann et al. 2022). Traditionally, these grazing pastures are burnt to promote the replacement of old dry grasses with young nutritious grasses (Grau et al. 2005; Gasparri and Baldi 2013), and this can explain the large amount of fires detected over the Wet Chaco's herbaceous covers. Furthermore, these managed fires occasionally get out of control and expand toward neighboring forests, producing disturbances that can lead to a replacement of the tree cover by shrublands (Landi et al. 2021; De Marzo et al. 2022). This transition often increases flammability facilitating future fire exposure and propagation.

The presence of one-time fires could be the result of either rare historical wildfires that occur only under specific climatic conditions or deforestation-related fires resulting in the replacement of forests for the previously mentioned LU. As it was mentioned in the introduction section, the detection of fires related to deforestation could differ in their timing depending on how they are used (as a deforestation tool by letting fires to advance over the forest, or as a clearing tool to burn the already cut biomass). None of these are common in Bolivia's and Paraguay's Chaco, where 92.1% and 84.7% of their respective forest loss were unrelated to BA detections. In contrast, among Argentina's deforested areas, almost 40% of its forest loss between 2001 and 2019 occurred over areas with at least one fire detection during the same period. These results suggest different

social, economic, or political factors in each country leading to distinct managements of the deforested land. While Argentina is using fire in some way to clear the natural forests and convert the land to other uses, Paraguay and Bolivia do not seem to use the same strategy.

Additionally, the analysis of the forest loss and fire events in the Chaco reveals that forest loss often precedes fires, with most of the forest loss occurring between the 3 years before a fire and the first year following a fire. This is likely the result of the regional practice of deforestation followed by the burning of dead biomass to make way for productive LU, as discussed by Gürtler (2009) and Andela et al. (2022). Regarding this time lag between fires and deforestation, the Wet Chaco showed noisier results, but still a clear trend of significant forest loss occurring before the fire.

Previous works have analyzed the effects of factors such as the quality of wood for charcoal or national policies over the decision of locals to cut forests or burn lands (Nolte et al. 2018; De Marzo et al. 2022; Estigarribia et al. 2023). Still, the reasons behind differences between countries or between regions remain unclear. In order to fully understand the drivers behind fires in the Chaco, it seems important to work in an interdisciplinary way, with anthropologists, economists, and other sciences, as we first need to interpret the factors affecting the decisions of locals to ignite fires.

Limitations

Our work has some limitations related to possible biases in the estimation of BA originating from the coarse resolution of the products we used. On the one hand, the 250-m pixels with fire detection in the FireCCI51 product are considered to burn completely when a determined adaptive threshold is reached. These thresholds and biases are described and informed in the product's User Guide (Pettinari et al. 2020), and they could add some over or under-estimation of BA depending on the case. Also, opposed to what was done by Lourenco et al. (2023), we decided not to filter the pixels by their confidence level as we found that over 94% of those classified as burnt had a confidence level over 70%, meaning that 6% of our pixels could have a lower confidence value, adding some biases to our BA values.

On the other side, the pixel size of the LandCoverCCI product (300 m) imply some uncertainties within classes and errors in the classification. To ease our work, in this study, we grouped LC classes considering the product's classes as pure. For this reason, we expect possible errors in the trees/grasslands/shrublands partition, affecting our results and interpretation of deforestation and other LCLUC. Particularly, in the case of the Wet Chaco, which has a very heterogeneous landscape with dispersed trees within grasslands, the burnt and unburnt tree cover could be more prone to errors than that of the more homogeneously distributed forests of the Dry Chaco.

These biases related to the spatial resolution of the products limited our interpretation of the size, duration, intensity, and expansion of each fire event. In order to study this in further detail, higher-resolution satellite imagery is required. Besides, other datasets containing information on each individual fire scale (within polygons in the shape of the fire) are available. Two good examples of these products are the FRY dataset, based on the MERIS Fire CCI4.1 and MODIS MCD64A1 (Laurent et al. 2018), and the Global Fire Atlas, based only on MODIS MCD64A1 (Andela et al. 2019). Further studies with these products could bring light into the specific drivers of fire size, duration, intensity, and expansion in the South American Chaco.

Conclusion

This study is the first attempt to assess fire events and their relationship with LC in the South American Chaco, comparing the characteristics of fire regimes, climate, and LC of the contrasting Dry and Wet Chaco. Based on satellite BA, LC, and meteorological products, we have shown that both subregions have seasonal variations of fires, with a unimodal seasonality found in the Dry Chaco (winter-spring fires) and a bimodal seasonality in the Wet Chaco (summer-autumn fires and winter-spring fires). All in all, the fire-affected area is mainly located in the Wet Chaco, but most LCC occurred in the Dry Chaco.

We were able to find strong links between LC types and fires, which could explain the discrepancies between the two subregions in terms of fire frequency and seasonality. Also, LC affects biomass production rates and the effect of meteorological variables on fuels.

Our study highlighted a further differentiation between the connection of fires to deforestation at the country level. This exposes the role of anthropic forcing, land management, and policy, as the use of fire differs from one country to the other.

To improve the identification of fire drivers, we suggest carrying out an analysis at the fire scale using products such as FRY (Laurent et al. 2018) or the Global Fire Atlas (Andela et al. 2019), combined with a Machine Learning or Deep Learning approach. Input variables should include the ones we used in this study (BA, LC, and climate variables) plus biomass information, vegetation indices, vegetation optical depth, socioeconomic variables, and government policies. Therefore, interdisciplinary studies are required if one wants to better assess and predict the impacts of environmental changes on fire activity. Such research should help policymakers take action to preserve and protect the remaining forests and wetlands of the Chaco.

Abbreviations

BA	Burnt area
CCI	Climate Change Initiative
CRU	Climatic Research Unit
EO	Earth Observation
ESA	European Space Agency
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
LC	Land cover
LandCoverCCI	ESA CCI MRLC product
LCC	Land cover change
LCLUC	Land cover and land use change
LU	Land use
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MRLC	Medium Resolution Land Cover
RS	Remote Sensing
UNFAO	United Nations Food and Agriculture Organization
VPD	Vapor-pressure deficit
WATCH	Water and Global Change
WFD	WATCH Forcing Data

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s42408-023-00212-4>.

Additional file 1: Supplementary Figure S1. Fire frequency by land cover type, calculated from filtering the total fire detections from the FireCCI51 product for the period 2001–2019 by the land cover types from the LandCoverCCI product, divided into 8 major groups of classes.

Additional file 2: Supplementary Figure S2. Annual temperature (top) and precipitation (bottom) anomalies from W5E5v2.0 for the Dry (left) and Wet (right) Chaco. The mean values for the period 2001–2019 were used as the baseline. Temperature time series include mean, average maximum and average minimum annual temperature anomalies.

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Authors' contributions

RSM collected and processed the data, analyzed the results, and drafted the manuscript. CO and AS conceived the idea and led the project. All co-authors discussed the results, provided critical feedback, and reviewed the manuscript.

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Availability of data and materials

ESA CCI MRLC (Defourny et al. 2023): <https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-land-cover> (last access on 18 April 2023). ESA CCI Fire v5.1 (Lizundia-Loiola et al. 2020): <https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-fire-burned-area> (last access on 18 April 2023).

W5E5v2.0 (Lange 2019; Cucchi et al. 2020): <https://data.isimip.org/10.48364/ISIMIP342217> (last access on 18 April 2023).

Declarations

Competing interests

The authors declare that they have no competing interests.

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