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Long term NDVI patterns of *Pinus* spp., *Salix* spp. and *Populus* spp. plantations in the Lower Delta of the Paraná River (Argentina)

Patrones de NDVI a largo plazo de plantaciones de *Pinus* spp., *Salix* spp. y *Populus* spp. en el Delta Inferior del río Paraná (Argentina)

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SUMMARY

Plantation forests are one of the main productive activities in the Lower Delta of the Paraná River. The plantation area corresponds to a wetland in which hydrological processes are a fundamental part of the landscape dynamics. However, forestation is also known for generating different environmental impacts, which must be understood in order to effectively manage it. In a context of studies at the regional scale, it is useful to identify the relationships between functional attributes of plantation forests and those derived from satellite images. The aim of this paper is to evaluate the use of remote sensing for the recognition of phenological patterns of *Pinus* spp., *Salix* spp. and *Populus* spp. forestation of the Paraná River Delta. We use medium spatial resolution satellite images for the period of 2008 to 2018. Normalized differential vegetation index (NDVI) patterns were analyzed through the use of geographic information systems and Google Earth Engine algorithms. NDVI records, by genus and by date, were used to generate seasonal, annual and monthly time series. The plantations showed a markedly seasonal response, with lower values in winter and higher values in spring/summer. *Pinus* spp. showed mean annual NDVI values higher than *Populus* spp. and *Salix* spp., according to its perennial (*Pinus* spp.) and semi-deciduous (Salicaceae) characteristics. New information and methodologies regarding the spectral responses of forestation in the region was obtained from large volumes of data available in the Cloud, which made it possible to understand in detail the phenological patterns of different types of forestation.

Keywords: forest ecosystem, multitemporal approach, vegetation indices, wetlands, Paraná River.

RESUMEN

Las plantaciones forestales son una de las principales actividades productivas del Delta Inferior del Río Paraná. El área de plantación corresponde a un humedal en el que los procesos hidrológicos son parte fundamental de la dinámica del paisaje. Sin embargo, las plantaciones forestales también se caracterizan por generar diferentes impactos en esta dinámica, los cuales deben ser conocidos para una gestión ambiental efectiva. En un contexto de estudios a escala regional, es útil identificar las relaciones entre los atributos funcionales de la cubierta arbórea y los derivados de las imágenes de satélite. El objetivo de este trabajo es evaluar el uso de sensores remotos para el reconocimiento de patrones fenológicos en plantaciones de *Pinus* spp., *Salix* spp. y *Populus* spp. del Delta del Río Paraná. Para ello se utilizaron imágenes satelitales de resolución espacial media para el período de 2008 a 2018. Los patrones de normalized differential vegetation index (NDVI) se analizaron mediante el uso de sistemas de información geográfica y algoritmos de Google Earth Engine. Se utilizaron registros de NDVI, por género y por fecha, para generar series temporales estacionales, anuales y mensuales. Las plantaciones mostraron una marcada respuesta estacional, con valores más bajos en invierno y más altos en primavera / verano. *Pinus* spp. mostró valores medios anuales de NDVI superiores a *Populus* spp. y *Salix* spp., de acuerdo con sus características perenne (*Pinus* spp.) y semicaducifolia (Salicaceae). Se obtuvo nueva información y metodologías sobre las respuestas espectrales de las forestaciones en la región, a partir de grandes volúmenes de datos disponibles en la Nube, lo que permitió conocer en detalle los patrones fenológicos de los diferentes tipos de forestación.

Palabras clave: ecosistema forestal, enfoque multitemporal, índices de vegetación, humedales, río Paraná.

INTRODUCTION

The Paraná River Delta region constitutes a complex floodplain with unique biogeographic and ecological characteristics, and can be considered a wetland macrosystem (Neiff and Malvárez 2004). In this area, forest plantations gained importance from the 1960s on, and is currently one of the main productive activities at the regional level (Kalesnik and Quintana 2006, Benzaquén 2013, Kalesnik *et al.* 2017). The species planted have changed as productive alternatives have emerged. The Salicaceae family covers the largest planted area and includes species such as *Salix nigra* Marshall, *S. matsudana* x *S. alba* cv., *S. babylonica* var. *sacramenta* (*Salix* spp.); *Populus deltoides* W. Bartram *ex* Marshall and *P. x canadensis* Moench (*Populus* spp.). *Pinus elliottii* Engelm. and *P. taeda* L. (*Pinus* spp.) can also be found to a lesser extent, especially when associated with sectors of wetland coastline (DNDFI 2019). The area destined for forestation is estimated at 78,843 ha (MAGyP 2018).

The ecological functions of wetlands differ from those of terrestrial ecosystems in their high dependence on the hydrological regime (Neiff *et al.* 2000). The change in land use associated with forestation generates environmental effects which are attributable on the one hand to the intrinsic action of the cultivated species, and on the other, to human management decisions (Neiff and Malvárez 2004). Given the ecohydrological characteristics of the region, forestry practices in the Lower Delta are frequently associated with anthropological changes in water management (Kalesnik *et al.* 2011). These changes alter the wetland hydrological regime, generating an increase in environmental risks associated with the loss of environmental, social and even economic services provided by wetlands (Benzaquén 2013). Therefore, it is necessary to develop and apply management strategies that consider the sustainability of the socio-productive system in conjunction with environmental sustainability (Kalesnik *et al.* 2017).

In order to contribute to sustainable forest management, it is convenient to specify the relationships between different functional attributes of the tree cover and those derived from satellite images (Paruelo 2008, Zamboni *et al.* 2017). In this context, geomatics offer tools for the study of land use and land cover, as well as tree phenology and inter and intra-annual variations due to climatic changes or events, which have consequences on functional parameters (Paruelo 2008). Furthermore, the use of remote sensing is a cost-effective method to collect data in large inaccessible areas, such as the Paraná River Delta, and provides an alternative source of information for extrapolating and estimating forest variables. It also allows researchers to work with large volumes of data and characterize land cover at different scales based on its functional response. The data obtained can be quickly updated and compared with existing data, and can be easily integrated with geographic information systems (GIS) (López-Sánchez *et al.* 2017, Zamboni *et al.* 2017).

The increasing availability of information derived from remote sensors, as well as the development of software, algorithms and tools for spatial analysis, optimize and generate synergies for the management of ecosystems. Google Earth Engine (GEE) is a cloud computing platform that makes possible the analysis of time series data derived from remote sensors, such as those from the Landsat missions (TM, ETM+ and OLI) (Wulder *et al.* 2019), and the development of algorithms for the estimation of Vegetation Indices, spectral signatures, among others (Gorelick *et al.* 2017). The multitemporal approach, based on the use of time series, contributes to the modeling of vegetation dynamics and its changes (Le Maire *et al.* 2011).

Vegetation Indices are synthetic variables associated with biophysical processes, derived from the analysis of land cover responses in different bands of images. The normalized differential vegetation index (NDVI) (Tucker 1979) is a widely used vegetation index in large-scale studies to determine vegetation dynamics (Meng *et al.* 2023) and responses of vegetation to climate (Gao *et al.* 2022). The NDVI time series show inter and intra annual variability and contrasted evolution according to location, scale and period (Piedallu *et al.* 2019). Thus, a series of indicator resources for the functional aspects of vegetation are available (Aceñolaza *et al.* 2014, Vanbeveren *et al.* 2016). Although there many studies that apply the NDVI in the Paraná River Delta (Zamboni 2017, Gaute *et al.* 2019), there are no records of its use in the study of long-term temporal dynamics and forest phenology at a regional scale. This is especially important because the region contains the highest concentration of Salicaceae plantations in the world (Cozzo 1995), and due to the necessity of developing tools that support forest management in environments that are complex as wetlands. The objective of this work is to evaluate the use of remote sensing for recognizing phenological patterns of forest plantations in wetland environments with a multitemporal approach.

METHODS

Study area. The Paraná River Delta is a region that spreads from Diamante city (Entre Ríos) to the limits of Buenos Aires city, located between the coordinates 32° 6’ 12.90” S as the upper limit, 34° 27’ 42.08” S as the lower limit, 60° 50’ 21.47” W west limit and 58° 14’ 30.14” W east limit. The total area covers approximately 17,500 km^2. The region forms an extensive and morphologically complex floodplain whose defined limits separate it from higher neighboring regions. The Delta is integrated into the Fluvio Littoral Complex with fluvial and tidal influence (Neiff and Malvárez 2004, Aceñolaza *et al.* 2008). The Lower Delta extends from the Ibicuy region to the La Plata estuary (figure 1).

The region has a heterogeneous landscape with a diversity of environments and physiognomies including an intricate hydrographic network. This hydrogeomorphological pattern determines the existence of areas subject to temporary or permanent waterlogging (Neiff *et al.* 2000, Kalesnik and Quintana 2006).

Forest layers were downloaded (MAGyP 2018), stored and analyzed, using Quantum GIS (version 3.6.1) with reference system EPSG: 5347 (POSGAR 2007 / Argentina 5). These layers were generated in inventories in 2008, 2013 and 2015, in ESRI Shapefile format. The data for 2008 was generated by Agroindustry (Ministerio de Agricultura, Ganadería y Pesca de la Nación, MAGyP) and those for 2013 and 2015 belong to the GIS and Forest Inventory Area (MAGyP) (Brandan *et al.* 2009, MAGyP 2018), and are freely distributed. Subsequently, plots of interest were selected and visited based on their presence on two or more dates during the temporal series studied (2008 - 2015 and 2008 - 2013).

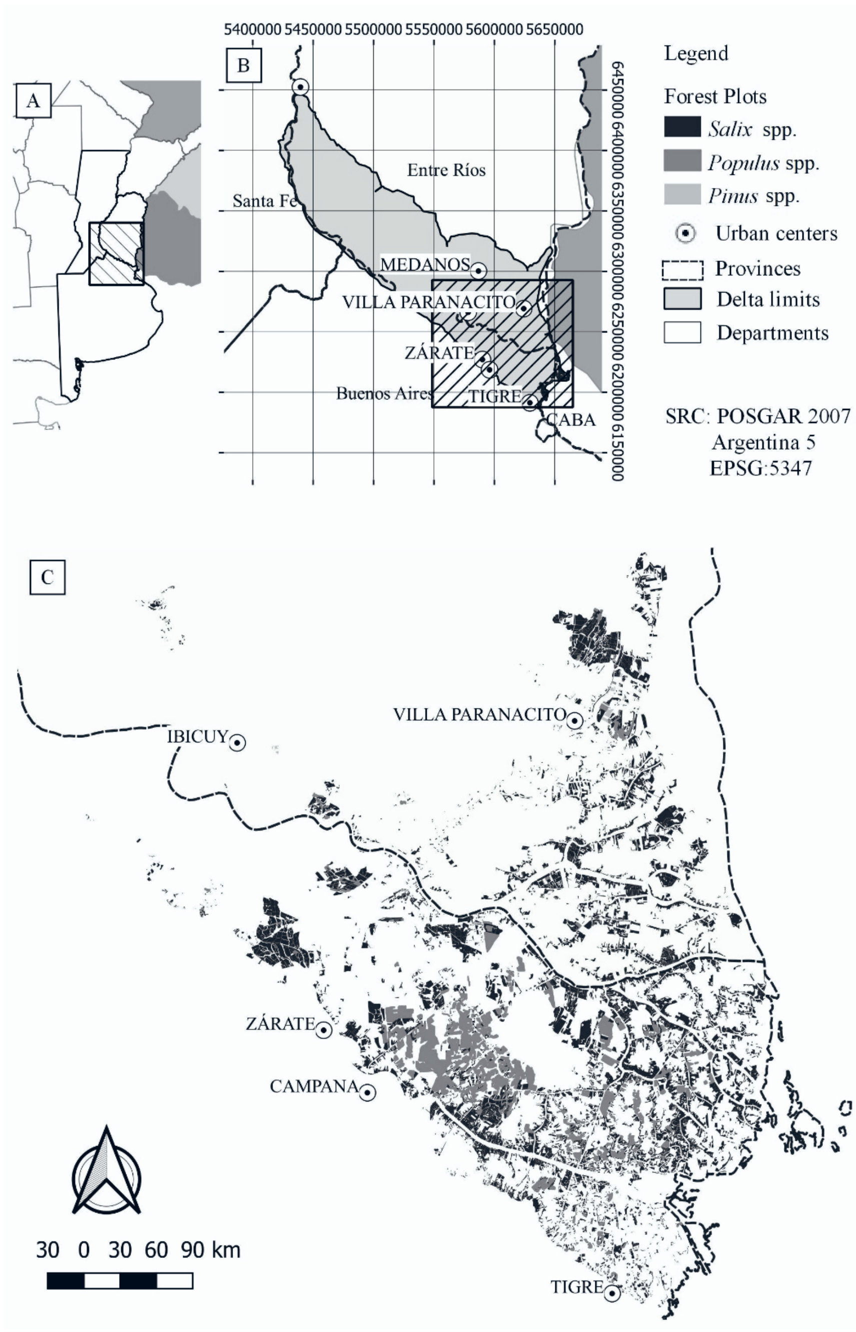

Figure 1. Location of the study area in the country (A), in the Lower Delta of the Paraná River (B) and the detail of the forested area (C). The plots shown are differentiated by genus. Adapted from Brandan *et al*. (2009) and MAGyP (2018).

Ubicación del área de estudio en el país (A), en el Delta Inferior del Río Paraná (B) el detalle del área forestada (C). Las parcelas mostradas están diferenciadas por género. Adaptado de Brandan *et al*. (2009) y MAGyP (2018).

NDVI time series. For the selected plots, time series of the NDVI were constructed from Google Earth Engine algorithms with data from the Landsat sensor. We worked with the Landsat collections LT5_L1T_TOA_FMASK, LE7_L1T_TOA_FMASK and LC8_L1T_TOA_FMASK, which are orthorectified and have a cloud and cloud shadow filtering algorithm (Fmask) (Zhu and Woodcook 2012) and top of atmosphere (TOA) correction. The period from 01-01-2008 to 31-12-2018 was considered as a time window for the analysis of pattern responses, including 215 scenes (biweekly frequency). Updated information is available for the forest plots identified in the inventories, as well as possible changes associated with management. The selected plots were grouped for analysis by genus (*Pinus* spp., *Salix* spp. and *Populus* spp.) and from these, Fusion Tables, tables whose format is compatible with GEE, were built.

The NDVI was calculated with the equation [1] (Tucker 1979):

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad [1]$$

where: NIR: near infrared band; Red: red band

The NDVI values vary between -1 and 1, where zero corresponds to an approximate value of no vegetation. Negative values represent areas without vegetation, while values close to 1 contain dense vegetation (Piedallu *et al.* 2019). The algorithm produced tables with NDVI values for each genus, by plot and date, in csv format.

Generation of the NDVI time series spatial database. The data of the NDVI time series obtained from GEE were incorporated into a SQLite database. From these data, tables were created with NDVI values, plot id, year, climatic season, month and day. R Studio ("RSQLite" and "sqldf" packages) was used to integrate the database into the GIS software. Three tables were obtained, for *Pinus* spp. (4,999 records), *Populus* spp. (283,540 records) and *Salix* spp. (1,454,927 records), respectively (table 1).

Statistical analysis. Summary variables, obtained by the statistical analysis of the NDVI time series, were grouped by genus. The Shapiro-Wilks test was carried out to analyze normality. Since the data did not present a normal distribution (W = 0.926; $P < 0.001$***), the variances were analyzed using the Kruskal-Wallis non-parametric statistical test (Balzarini *et al*. 2008). The variances were compared by season, year, month and dates. To determine in which season, year and month there were differences, Multiple Range tests were performed, which determine significant differences and identify homogeneous phenological behavior groups (Balzarini *et al*. 2008).

RESULTS

In total, 4,999 NDVI records were obtained for *Pinus* spp., 283,540 for *Populus* spp. and 1,454,927 for *Salix* spp. (table 2). Due to cloudiness, not all years and seasons were equally evaluated. The mean was 0.6 for the three

Table 1. Summary of NDVI time series (TS). Null records correspond to plots with no data due to cloud presence.

Resumen de la serie temporal (ST) del NDVI. Los registros nulos corresponden a parcelas en las que no se obtuvieron datos para por la presencia de nubes.

File	Total records	Valid records	Null records
Pinus spp. NDVI TS	5,419	4,999	420
Populus spp. NDVI TS	401,568	283,540	118,028
Salix spp. NDVI TS	2,089,623	1,454,927	634,696

Table 2. Statistical summary of NDVI by genus.

Resumen estadístico de NDVI por género.

NDVI	*Pinus* spp.	*Populus* spp.	*Salix* spp.
N	4,999	283,540	1,454,927
Mean	0.6	0.6	0.6
Standard Deviation	0.09	0.14	0.13
Coefficient of Variation (%)	15	23	23
Standardized Bias	-36	12,555	$1.74E^{+06}$
Standardized Kurtosis	31	38	274

species, which is within the expected values for this type of coverage (Alvares *et al.* 2013). The standard deviation was also similar for the three species, while the Coefficient of Variation was lower for *Pinus* spp. (15 %) than for Salicaceae (23 %). Standardized Bias and Standardized Kurtosis can be used to determine whether the sample is from a normal distribution. Values outside the range of -2 to +2 indicate significant deviations from normality, which would tend to invalidate any statistical tests with reference to the standard deviation (Perez-Arevalo and Velázquez-Martí 2018). In this case, the standardized bias and standardized kurtosis values are not within the expected range for data from a normal distribution.

NDVI time series by climatic season. The three species presented lower NDVI values in winter (0.57 for *Pinus* spp., 0.41 for *Populus* spp. and 0.42 for *Salix* spp.), with tendencies to increase towards summer (figure 2), reaching a maximum of 0.66 for *Pinus* spp., 0.68 for *Populus* spp. and 0.67 for *Salix* spp. The Salicaceae genera planted presented the lowest values in winter and the highest in summer, compared to *Pinus* spp., which presented lower intra-annual variation due its perennial characteristics.

The NDVI values of *Pinus* spp. showed significant differences between seasons, except between autumn and summer, which presented the higher values (KW: n = 4,999; H = 522; $P < 0.05^*$; α = 0.05). The NDVI values of *Populus* spp. (KW: n = 283,540; H = 120,570; $P < 0.05^*$; α = 0.05) and *Salix* spp. (KW: n = 1,454,927; H = 609,806; $P < 0.05^*$; α = 0.05) showed significant differences between all seasons.

NDVI time series per year. NDVI mean values ranged from a minimum of 0.59 to a maximum of 0.66 for *Pinus* spp., from 0.56 to 0.62 for *Populus* spp. and from 0.55 to 0.61 for *Salix* spp. (figure 3). In general, *Pinus* spp. presented annual values higher than the Salicaceae, except in 2008, where the three species responded in a similar way. As mentioned previously, *Pinus* spp. shows a lower intra-annual variation, so its mean is less affected by low NDVI values (in winter), unlike the Salicaceae. These showed a similar behavior over the years, but *Salix* spp. presented lower values than *Populus* spp. *Pinus* spp. showed an increasing trend in NDVI over the years, only declining in 2016, while *Salix* spp. and *Populus* spp. show a steady trend.

Pinus spp. presented significant differences between the average annual NDVI values (KW: n = 4,999; H = 201; $P < 0.05^*$; α = 0.05) with the initial (2008) and final (2017) years of the temporal series showing lower and higher values respectively, thus differentiating themselves from the others. *Populus* spp. (KW: n = 283,540; H = 2,540; $P < 0.05^*$; α = 0.05) and *Salix* spp. (KW: n = 1,454,927; H = 17,590; $P < 0.05^*$; α = 0.05) had significant differences in NDVI between all years.

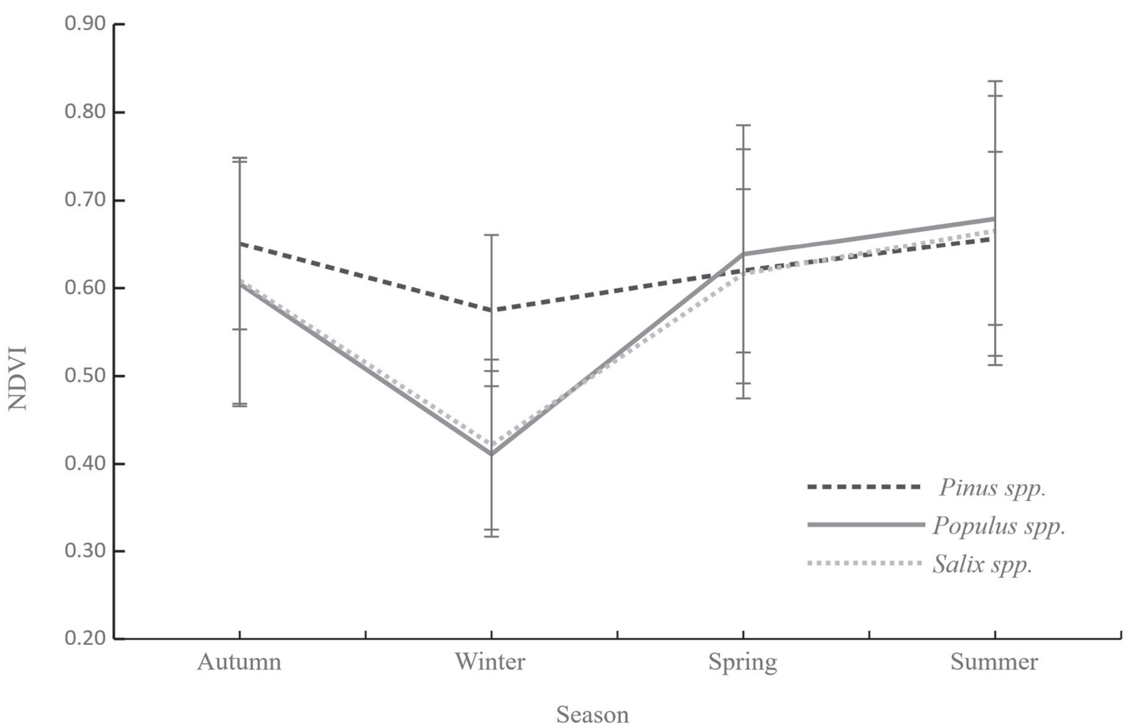

Figure 2. Time series of mean NDVI values of each genus by season. The error bars correspond to the Coefficient of Variation.

Series temporales de valores medios de NDVI para cada género por estación. Las barras de error corresponden al Coeficiente de Variación.

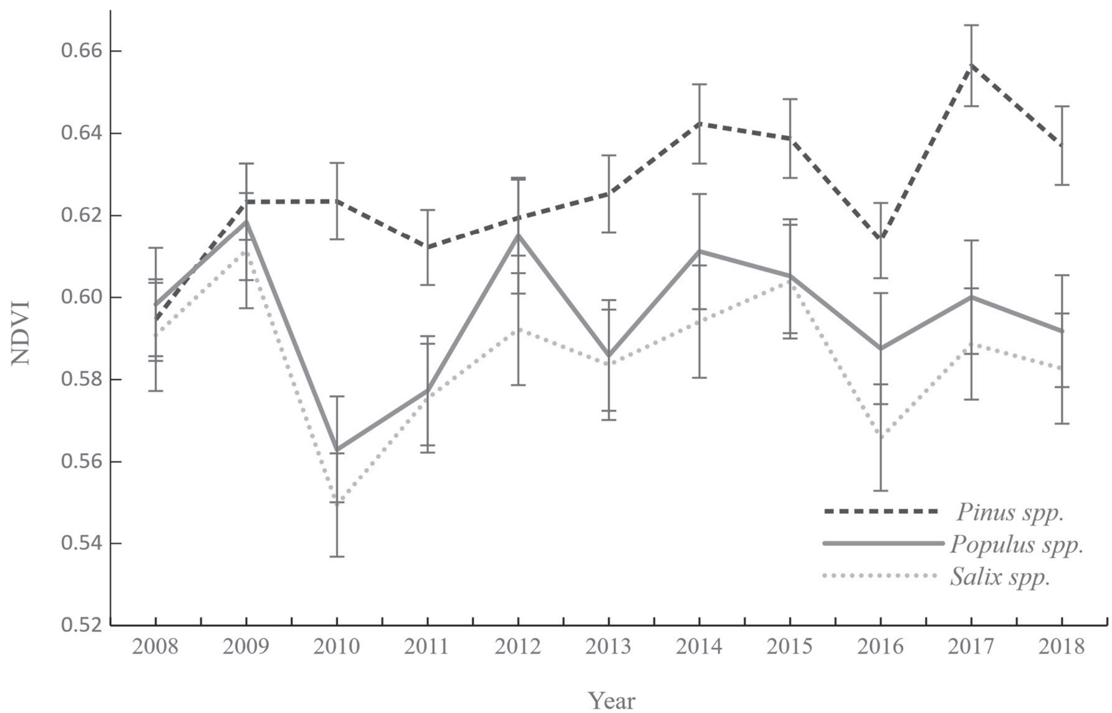

Figure 3. Time series of mean NDVI values of each genus by year. The error bars correspond to the Coefficient of Variation.

Series temporales de valores medios de NDVI para cada género por año. Las barras de error corresponden al Coeficiente de Variación.

NDVI time series per month. The three genera presented the lowest values in July, which corresponds to winter (0.56 for *Pinus* spp., 0.38 for *Populus* spp. and 0.39 for *Salix* spp.), and showed an increasing trend towards spring and summer, with *Pinus* spp. reaching its higher values in February (0.67), *Populus* spp. in November (0.71) and *Salix* spp. in January and November (0.67) (figure 4). *Pinus* spp. showed superior values to the Salicaceae from February to September and less NDVI variation between months. *Salix* spp. and *Populus* spp. exceeded the maximum values reached by *Pinus* spp. (0.65) from October to January and presented similar values between them.

The NDVI values of *Pinus* spp. showed significant differences between months (KW: n = 4,999; H = 769; $P < 0.05^{*}$; α = 0.05). In the analysis of homogeneous groups, the months of December and January (summer), April and May (autumn) did not present significant differences, as evidenced in the seasonal analysis. In the case of *Populus* spp., there were significant differences between all months (KW: n = 283,540; H = 159,065; $P < 0.05^{*}$; α = 0.05). *Salix* spp. also presented significant differences between the months (KW: n = 1,454,927; H = 751,090; $P < 0.05^{*}$; α = 0.05), except between February / December, March / April, June / July.

NDVI time series by date. In figure 5 the complete time series of mean NDVI values for all available dates considered in the study is shown. This graph allowed to understand the response of vegetation in detail and to identify the moments in which values with greater dispersion with respect to the mean occurred, which indicate different behavior from the typical response pattern. This type of situation is of great relevance for productive management since it provides warnings about alterations that can be dealt with more efficiently through early identification.

DISCUSSION

The results of the NDVI time series pattern coincide with those found by Alvares *et al.* (2013), who estimated a mean NDVI of 0.6 for Loblolly pine (*Pinus taeda*) plantations in temperate areas of Brazil. These values are lower than those estimated by Le Maire *et al.* (2011), which are mean NDVI values of 0.8 for *Eucalyptus* spp. for the same region. The difference in values is associated with the differential growth rates of the species. Dispersion measures (Standard Deviation, Coefficient of Variation) are lower in *Pinus* spp. than in the other genera, which is possibly associated with its evergreen characteristics, as its values would fluctuate less throughout the year. The annual average production oscillates between 20-25 m^3 ha^{-1} $year^{-1}$ for *Populus* spp., 15-20 m^3 ha^{-1} $year^{-1}$ for *Salix* spp. and ≈ 32 m^3 ha^{-1} $year^{-1}$ for *Pinus* spp. (Cerrillo *et al.* 2015), while *Eucalyptus* spp. shows production of ≈ 40 m^3 ha^{-1} $year^{-1}$, explaining the higher mean NDVI values in this species (Sepliarsky 2002).

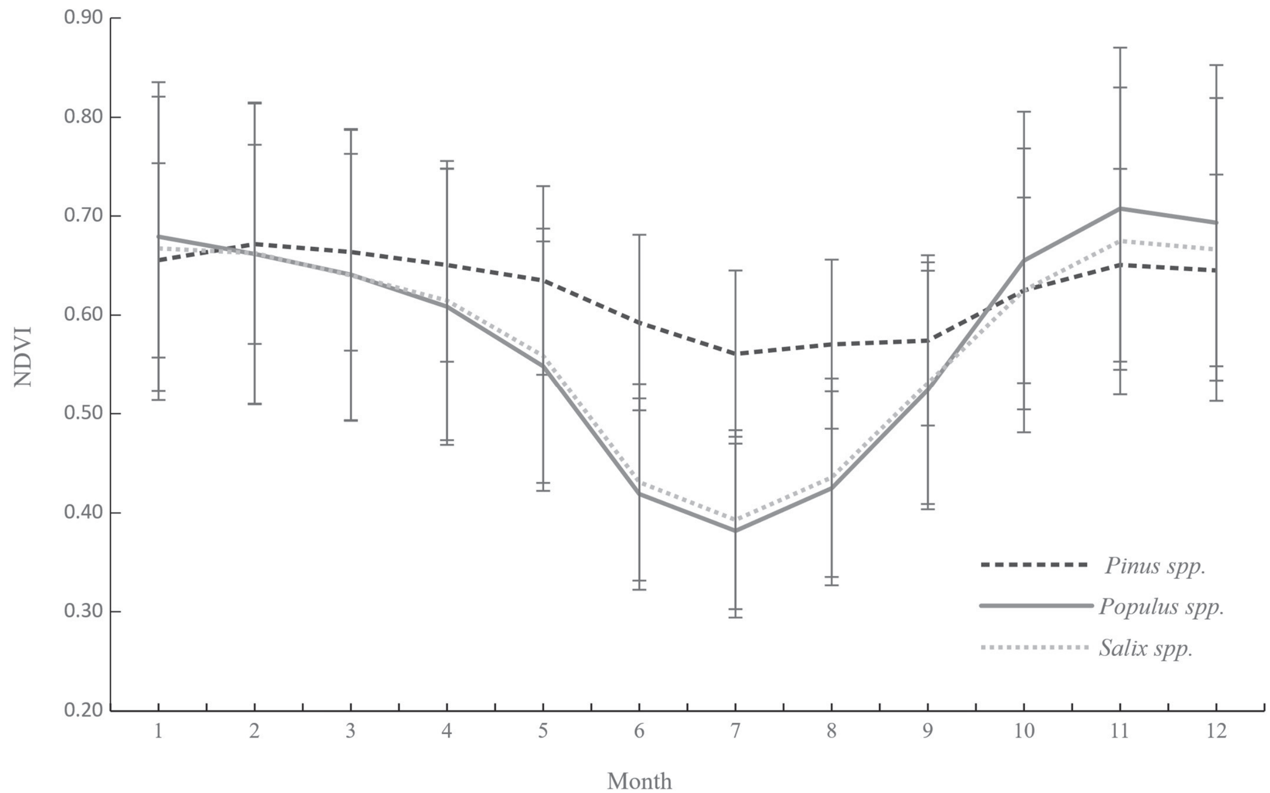

Figure 4. Time series of mean NDVI values of each genus by month. The error bars correspond to the Coefficient of Variation.

Series temporales de valores medios de NDVI para cada género por mes. Las barras de error corresponden al Coeficiente de Variación.

Since *Pinus* spp. species are perennial, their seasonal and monthly variation was lower, presenting higher NDVI values in autumn and summer. Increasing trends in NDVI are most often attributed to lengthening of the growing season due to warmer weather, which increases plant photosynthesis (Piedallu *et al.* 2019). Authors such as Vanbeveren *et al.* (2016) observed similar seasonal patterns for *Populus* spp. They assured that the phenological quantification using remote sensing (Vegetation Indices) is triggered by introducing a different color palette to the observed area, this occurring during the green-up. In the case of the Salicaceae, the increasing values from winter to summer are related to the fact that these are deciduous species, so the loss of leaves in autumn causes the NDVI to decrease significantly in winter. In spring, the recovery of foliage and the increase in photosynthetic activity cause the NDVI to increase until it reaches a maximum in the summer (Piedallu *et al*. 2019), a pattern that was also observed in this study.

Annual records can be compared with climatic data such as the years of occurrence of El Niño (ENSO's floods) and La Niña (Neiff *et al.* 2000). The low NDVI response in 2008 for *Pinus* spp., *Salix* spp. and *Populus* spp. is associated with the extraordinary drought of that year, which produced a decrease in photosynthetic activity due to water stress (Scarpati and Capriolo 2013). The increasing values of *Pinus* spp. through the years can be explained by the cumulative growth of the plantations. For Salicaceae, the maximum value was observed in 2009 and the minimum in 2010. This decrease in NDVI values could have two explanations. The presence of water in the plots interferes with the measurement of the index, causing its values to decrease. Flooding can have negative effects on forestation, including reductions in the rate of formation and expansion of new leaves, reduction of photosynthetically active leaf area due to acceleration of senescence and leaf abscission, among others (Luquez *et al.* 2018). However, *Salix* species are naturally adapted to flooded areas, so they tend to grow in low microsites prone to flooding. The year 2010 was associated with a strong Oceanic Niño Index (ONI) (NOAA 2019), which is correlated with the occurrence of wet cycles and flood events (Neiff *et al.* 2000). *Pinus* spp. was not affected by these events as it is planted in topographically non-flooding areas due to its low tolerance to flood.

Unlike the mean annual NDVI series, in the date time series we observed similar behavior of the species on more than one date. This similarity in the NDVI behavior at the regional level is associated with the coupling of vegetation greenness and the region's hydrogeomorphological characteristics (Zamboni 2017). NDVI is associated with the leaf area of the vegetation and its chlorophyll content,

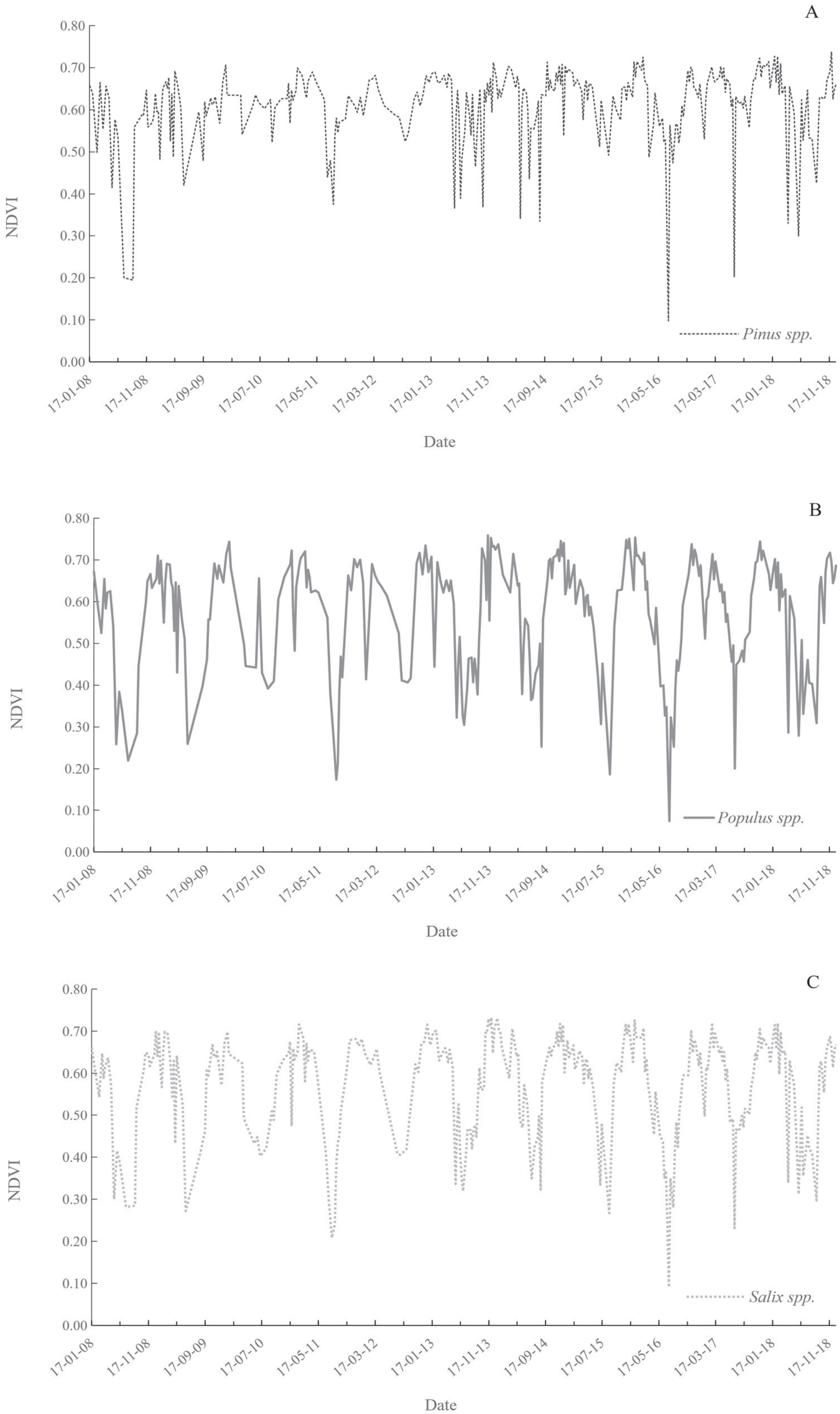

Figure 5. Time series of mean NDVI values for all available dates for *Pinus* spp. (A), *Populus* spp. (B), and *Salix* spp. (C).

Series temporales de valores medios de NDVI para todas las fechas disponibles de *Pinus* spp. (A), *Populus* spp (B), y Salix spp. (C).

therefore it varies according to vegetation type, vegetation coverage, soil type, geomorphology, and other variables (Piedallu *et al.* 2019).

CONCLUSIONS

Phenological patterns in forest plantations of the Paraná River Delta were successfully analyzed using satellite images of medium spatial resolution for the period 2008 to 2018. Google Earth Engine permitted the characterization and monitoring of forest systems through the NDVI time series.

Valuable information and methodology regarding the spectral responses of the region's forestation was obtained from large volumes of data available in the cloud and processed semi-automatically. This can be used as a reference for the region and be contrasted with other data collections to improve the precision of the estimates of a plot of interest, identify changes and establish early warning systems. These products can be used as support tools for decision-making by foresters and managers to understand and monitor changes in forest productivity and evaluate the consequences of land use in a context of climate change.

A strong inter and intra-annual variation of the NDVI was observed for the three species. The intra-annual variation was markedly seasonal, so the response is associated with the seasonality of factors such as river water level, temperature and photoperiod. On the other hand, the interannual variability could be explained by climatic data such as the occurrence of El Niño and La Niña. The NDVI also allowed *Pinus* spp. to be differentiated from *Populus* spp. and *Salix* spp., as it presented higher values throughout the time series, while the Salicaceae presented similar behavior and lower values.

The availability of data from a relatively long period of time made it possible to understand in detail the response pattern of different types of forestation, providing valuable information for environmental management. The data at plot level are of great interest for production and may be used in research that require classifications, productivity estimation, comparison with biophysical and environmental parameters, among others.

AUTHOR CONTRIBUTION

Virginia Piani developed the idea, carried out the data collection, analyzed the results and wrote the manuscript, Lisandra P Zamboni analyzed the results and wrote the manuscript, Francisco Viva Mayer developed the algorithms and revised the manuscript, Walter F Sione and Pablo G Aceñolaza reviewed the manuscript.

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REFERENCES

Aceñolaza PG, LP Zamboni, WF Sione, F Kalesnik. 2008. Caracterización de la región superior del Complejo Litoral del Río Paraná: grandes unidades de ambiente. *Instituto Superior de Correlación Geológica Serie Miscelánea* 17(2): 293-308.

Aceñolaza PG, LP Zamboni, F Kalesnik, EE Rodríguez, WF Sione, C Serafini. 2014. Mapa de cobertura de suelo para un sector del norte del Complejo Fluvio/Litoral del Río Paraná con herramientas de geomática. UD y la Geomática 8: 39-44. Consultado 01 Jul. 2023. Disponible en https://ri.conicet.gov.ar/handle/11336/80272

Alvares CA, JSB Munhoz, JL Stape, J Stahl, L Andrade, G Santos, KT Borba. 2013. Caracterização da dinâmica dos índices de vegetação NDVI e EVI em plantações de *Pinus* do Brasil. *In* Epiphanio JCN, LS Galvão eds. Anais XVI Simpósio Brasileiro de Sensoriamento Remoto-SBSR. Foz do Iguaçu, PR, Brasil. p. 2866-2873.

Balzarini MG, L González, M Tablada, F Casanoves, JA Di Rienzo, CW Robledo. 2008. InfoStat. Manual del Usuario. Córdoba, Argentina. Editorial Brujas. 336 p.

Benzaquén L. 2013. Inventario de los humedales de Argentina: Sistemas de paisajes de humedales del Corredor Fluvial Paraná-Paraguay. Argentina. Secretaría de Ambiente y Desarrollo Sustentable de la Nación. 376 p.

Brandan S, L Corinaldesi, L Frisa. 2009. Sector Forestal. Año 2008. Argentina. Ministerio de Agricultura, Ganadería y Pesca. 38 p.

Cerrillo T, JA Álvarez, JL Álvarez, A Battistella, C Braccini, E Casaubón, D Ceballos, S Cortizo, E Fernandez Tschieder, P Fernández, L Faustino, N Fracassi, M García Cortés, A González, L Grieco, A Hemming, L Landi, V Mangieri, V Mema, S Monteverde, G Mujica, D Olemberg. 2015. La forestación de salicáceas como aporte al desarrollo sustentable del Delta del Paraná. *In* XXIX Jornadas Forestales de Entre Ríos. Concordia, Argentina. p. 1-14.

Cozzo D. 1995. Silvicultura de plantaciones maderables. Buenos Aires, Argentina. Orientación Gráfica Editora S.R.L. 905 p.

DNDFI (Dirección Nacional de Desarrollo Foresto Industrial, AR). 2019. Inventario nacional de plantaciones forestales por superficie. Accessed 10 Jan. 2019. Available in https://datos.agroindustria.gob.ar/dataset/inventario-nacional-plantaciones-forestales-por-superficie

Gao W, C Zheng, X Liu, Y Lu, Y Chen, Y Wei, Y Ma. 2022. NDVI-based vegetation dynamics and their responses to climate change and human activities from 1982 to 2020: A case study in the Mu Us Sandy Land, China. *Ecological Indicators* 137: 108745. DOI: https://doi.org/10.1016/j.ecolind.2022.108745

Gaute M, R Benítez, H Fassola, T Boca, E Andenmatten. 2019. Caracterización de plantaciones forestales a partir de información derivada de plataformas satelitales y recursos informáticos de alto rendimiento. *In* XIX Jornadas Técnicas Forestales y Ambientales. Eldorado, Argentina. p. 1-4.

Gorelick N, M Hancher, M Dixon, S Ilyushchenko, D Thau, R Moore. 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment* 202: 18-27. DOI: https://doi.org/10.1016/j.rse.2017.06.031

Kalesnik F, R Quintana. 2006. El Delta del Río Paraná como un mosaico de humedales. Caso de estudio: La Reserva de Biosfera MAB-UNESCO "Delta del Paraná". *Revista UnG-Geociências* 5(1): 22-37.

Kalesnik F, P Aceñolaza, M Hurtado, J Martínez. 2011. Relationship between vegetation of the levee neo-ecosystems and environmental heterogeneity in the Lower Delta of the Paraná River, Argentina. *Water and environment Journal* 25(1): 88-98. DOI: https://doi.org/10.1111/j.1747-6593.2009.00196.x

Kalesnik F, R Vicari, P Aceñolaza, H Sirolli, L Bonan, L Iribarren, M Ramello, J Valle, R Bó. 2017. Restauración ecológica en humedales. Conservación y desarrollo sustentable en el Delta del Paraná. *In* Zuleta GA, AE Rovere, FP Mollard eds. SIACRE-2015: Aportes y Conclusiones. Tomando decisiones para revertir la degradación ambiental. Buenos Aires, Argentina. Vázquez Mazzini Editores. p. 193-202.

Le Maire G, C Marsden, Y Nouvellon, C Grinand, R Hakamada, JL Stape, JP Laclau. 2011. MODIS NDVI time-series allow the monitoring of *Eucalyptus* plantation biomass. *Remote Sensing of Environment* 115(10): 2613-2625. DOI: https://doi.org/10.1016/j.rse.2011.05.017

López-Sánchez CA, P Garcia-Ramirez, R Resl, JC Hernandez-Diaz, PM Lopez-Serrano, C Wehenkel. 2017. Modelling dasometric attributes of mixed and uneven-aged forests using Landsat-8 OLI spectral data in the Sierra Madre Occidental, Mexico. *iForest-Biogeosciences and Forestry* 10: 288-295. DOI: https://doi.org/10.3832/ifor1891-009

Luquez VMC, T Cerrillo, ME Rodríguez. 2018. Tolerancia a la inundación en sauces plantados en la Argentina: conocimiento actual y perspectivas. *Revista de la Facultad de Agronomía* 117(1): 89-98.

MAGyP (Ministerio de Agricultura Ganadería y Pesca, AR). 2018. Cartografía del Inventario Nacional de Plantaciones Forestal de Macizos Forestales. Accessed 15 Feb. 2018. Available in https://geoadmin.magyp.gob.ar/geonetwork/srv/spa/catalog.search;jsessionid=80531F1A05FEFF9741B04A104A929507.192.168.162.144#/metadata/0cbd887a-fe79-4e97-8f9f-2735365800b1

Meng Y, B Hou, C Ding, L Huang, Y Guo, Z Tang. 2023. Spatiotemporal patterns of planted forests on the Loess Plateau between 1986 and 2021 based on Landsat NDVI time-series analysis. *GIScience & Remote Sensing* 60(1): 2185980. DOI: https://doi.org/10.1080/15481603.2023.2185980

Neiff JJ, M Mendiondo, C Depettris. 2000. ENSO Floods on River Ecosystems: Catastrophes or Myths?. *In* Toenmsnann F, M Koch eds. River Flood Defence. Kassel Reports of Hydraulic Engineering, No. 9. Kassel. Herkules Verlag. p. 141-152.

Neiff JJ, AI Malvárez. 2004. Grandes humedales fluviales. *In* Malvárez AI, RF Bó eds. Documentos del curso-taller: Bases ecológicas para la clasificación e inventario de humedales en Argentina. Buenos Aires, Argentina. FCEyN, Ramsar. p. 77-87.

NOAA (National Oceanic and Atmospheric Administration, EE UU). 2019. Cold and Warm Episodes by Season. Accessed 2 jul. 2019. Available in http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml

Paruelo JM. 2008. La caracterización funcional de ecosistemas mediante sensores remotos. *Ecosistemas* 17(3): 4-22.

Perez-Arevalo JJ, B Velázquez-Martí. 2018. Evaluation of pruning residues of *Ficus benjamina* as a primary biofuel material. *Biomass and Bioenergy* 108: 217-223. DOI: https://doi.org/10.1016/j.biombioe.2017.11.017

Piedallu C, V Chéret, JP Denux, V Perez, JS Azcona, I Seynave, JC Gégout. 2019. Soil and climate differently impact NDVI patterns according to the season and the stand type. *Science of the Total Environment* 651: 2874-2885. DOI: https://doi.org/10.1016/j.scitotenv.2018.10.052

Scarpati OE, AD Capriolo. 2013. Sequías e inundaciones en la provincia de Buenos Aires (Argentina) y su distribución espacio-temporal. *Investigaciones Geográficas, Boletín del Instituto de Geografía* 82: 38-51. DOI: https://doi.org/10.14350/rig.31903

Sepliarsky F. 2002. Producción y mercado de madera de *Eucalyptus grandis*. *In* XVII Jornadas Forestales De Entre Ríos. Concordia, Argentina. p. 1-9.

Tucker CJ. 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment* 8(2): 127-150. DOI: https://doi.org/10.1016/0034-4257(79)90013-0

Vanbeveren SP, J Bloemen, M Balzarolo, LS Broeckx, I Sarzi-Falchi, MS Verlinden, R Ceulemans. 2016. A comparative study of four approaches to assess phenology of *Populus* in a short-rotation coppice culture. *iForest-Biogeosciences and Forestry* 9(5): 682. DOI: https://doi.org/10.3832/ifor1800-009

Wulder MA, TR Loveland, DP Roy, CJ Crawford, JG Masek, CE Woodcock, J Dwyer. 2019. Current status of Landsat program, science, and applications. *Remote Sensing of Environment* 225: 127-147. DOI: https://doi.org/10.1016/j.rse.2019.02.015

Zamboni LP. 2017. Dinámica del fuego en el Complejo Litoral del Río Paraná, integrando información satelital y del terreno. Tesis Doctorado en Ciencias Biológicas. Salta, Argentina. Universidad Nacional de Salta. 98 p.

Zamboni LP, WF Sione, FR Tentor, PG Aceñolaza. 2017. Cartografía de modelos combustibles en el Complejo Fluvio Litoral del Río Paraná a partir de datos de terreno y derivados de sensores remotos. *Scientia Interfluvius* 8(2): 65-77.

Zhu Z, CE Woodcock. 2012. Object-based cloud and cloud shadow detection in Landsat imagery. *Remote Sensing of Environment* 118: 83-94. DOI: https://doi.org/10.1016/j.rse.2011.10.028

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