

# Assessment of land use change in the dryland agricultural region of Córdoba, Argentina, between 2000 and 2020 based on NDVI data

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## ABSTRACT

The dryland region of Córdoba province experienced a strong increase in agricultural land-use in the 21st century. Between years 2000 and 2020 the temporal variation of land-use measures derived from the seasonal variation curve of the Normalized Difference Vegetation Index (NDVI) was analyzed. In eleven departments of the region, the following NDVI measurements were obtained for each crop cycle from September to April: minimum value (NDVIn), maximum value (NDVix), amplitude (NDVIa=NDVix-NDVIn) and mean value (NDVIm). The sowing percentage per department was analyzed spatially and temporally, as well as the land use indicators. Both NDVIn and NDVix are related to the sowing area per department, determining a negative correlation (-0.36) for NDVIn and a positive one (0.596) for NDVix. The positive correlation with NDVIa (0.569) is considered directly linked to the agricultural land use. The seasonal variation of the NDVI showed changes over time, which were compatible with the increase in agricultural activity in the region. Although the increase in agricultural land use was noticeable through both the decrease in NDVIn and the increase in NDVix, along with a general trend towards rising NDVIa values, the variation was more apparent in those departments where agricultural activity increased to a greater proportion.

**Keywords:** soybean, corn, temporal trend, sustainability

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## RESUMEN

La región de secano de la provincia de Córdoba experimentó un fuerte aumento en el uso agrícola del suelo en el siglo XXI. Se analizó la variación entre los años

2000 y 2020 de diferentes medidas relacionadas al uso del suelo derivadas de la curva de variación estacional del Índice de Vegetación de la Diferencia Normalizada (IVDN). En once departamentos de la región se obtuvieron las siguientes mediciones del NDVI de septiembre a abril: mínimo (IVDNn), máximo (IVDNx), amplitud (IVDNa=IVDNx-IVDNn) y valor medio (IVDNm). Se estableció espacial y temporalmente el porcentaje departamental de siembra y del conjunto de indicadores de uso del suelo. Tanto IVDNn como IVDNx están relacionados con la superficie departamental de siembra, determinando una correlación negativa (-0,36) para IVDNn y positiva (0,596) para IVDNx. La correlación positiva con IVDNa (0,569) se considera ligada de manera directa al uso agrícola del suelo. La variación del IVDN muestra cambios a través del tiempo, compatibles con el aumento de la actividad agrícola en la región, que se evidencia tanto por la disminución del IVDNn, el aumento del IVDNx y una tendencia positiva de IVDNa, más evidente en aquellos departamentos donde la actividad agrícola incrementó el uso del suelo en mayor proporción.

**Palabras clave:** soja, maíz, tendencia temporal, sustentabilidad

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## INTRODUCTION

In the central region of Argentina rainfall amounts fluctuated notably throughout the 20th century, with negative rainfall anomalies until the 1960s that became positive thereafter (De la Casa, Ovando and Díaz, 2018). The combined effect of deforestation, overgrazing, as well as inappropriate tillage technologies, under extremely dry and windy weather conditions, produced severe dust storms during the 1930s and 1940s, that caused livestock mortality, crop failure, economic bankruptcy of productive systems and migration of the rural population. The increased rainfall during the second half of the last century, on the other hand, led to the conversion of abandoned farmlands into grazing or cultivated land (Viglizzo and Frank, 2006).

The decrease in water deficiency during the second half of the 20th century increased the productive potential of the dryland agricultural region of Córdoba (Magrin et al., 2005; De la Casa and Ovando, 2014). This change towards a more favorable climatic condition is explained by the sustained increase in the rainfall regime (Sierra et al., 1994; Viglizzo et al., 1995; Liebmann et al., 2004; González et al., 2013; De la Casa, Ovando and Díaz, 2018), rather than by an alteration

in the atmospheric demand for water (De la Casa and Ovando, 2016). Long-term climatic variation, together with the development of more adapted technologies to sub-humid and semi-arid environments, such as no-tillage farming, had a great impact on agricultural activity, such that agricultural production increased steadily since the 1960s in detriment of livestock, which had been the predominant activity during the 20th century (Viglizzo and Frank, 2006).

The positive phase of the rainfall regime is explained, in some cases, as the result of a climatic jump that, associated with the phenomenon of global warming, would have permanent consequences (Minetti and Vargas, 1997). Alternatively, an even greater concern arises from a pendular (Suriano and Ferpozzi, 1993) or oscillating conception of rainfall (De la Casa and Nasello, 2010; De la Casa, Ovando and Díaz, 2018), since a negative phase of the rain cycle should follow the current positive phase. According to the agroecological history of the region, the substitution of livestock production by agriculture can be detrimental both in environmental and economic terms, thus a permanent monitoring and evaluation of land-use is justified.

Viglizzo et al. (2001) used a set of indicators to assess the sustainability of agricultural production

systems. Land-use and the application of technology are the major determinants of rural environment sustainability, since they influence the functionality of agroecosystems. Among different indicators proposed, in the first place Viglizzo et al. (2003) employed land-use due to its great agroecological relevance, consequently, it is necessary to develop procedures that carry out permanent monitoring of land-use and evaluate their changes over time. In addition to the conventional information from surveys and censuses, it is currently feasible to monitor land-use from radiometric data, a procedure that requires a prior reliable interpretation of the satellite signal (Fox et al., 2017). Procedures that apply radiometric data have been gaining ground as satellite information is not only increasingly available at different scales of spatial detail, but also because the series are more extended over time and allow temporal inspection of data (Guida-Johnson and Zulueta, 2013).

The spectral vegetation indices (VI), such as the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Soil Adjusted Vegetation Index (SAVI), or Wide Dynamic Range Vegetation Index (WDRVI), set up simple expressions useful to monitor the crops condition and productivity (Becker-Reshef et al., 2010; Sakamoto et al., 2014; Saeed et al., 2017; Seo et al., 2019; Liu et al., 2020; Nolasco et al., 2021). Likewise, the temporal dynamics of VI also allows us to identify phenological changes that the vegetation experiences over time (Zhang et al., 2003). Different time series analysis procedures, HANTS (Verhoef, W., 1996), TIMESAT (Jönsson and Eklundh, 2004; Udelhoven, 2011), among others, have been developed using spectral indicators as a proxy for vegetation, in order to identify most characteristic moments of the evolution and seasonal changes of the vegetation. Jayawardhana and Chathurangeb (2016) extracted parameters from NDVI-MODIS time series to characterize the different agroecological zones of Sri Lanka, and Brown et al. (2010) analyzed the phenological dynamics of the vegetation in Africa in response to the most preponderant climatic oscillations in the region.

More specifically, Sakamoto et al. (2010) proposed a procedure to detect the succession of phenological stages in corn and soybean from the analysis of WDRVI data from the MODIS instrument. On the other hand, Seo et al. (2019) referred to the parameters of the beginning, end and peak of the season to represent the phenology of corn and soybean crops. The peak of greenness or maximum value of the NDVI curve is one of the indicators that these algorithms use to represent the productive potential of the vegetation (Skakun

et al., 2019; Stepanov et al., 2020). Also, its occurrence constitutes a phenological reference that, associated with the reproductive stages of flowering, tasseling or silking in maize and pod establishment in soybean, constitutes a critical period for crops due to their high sensitivity to lack of water (Sakamoto, 2020; Wan et al., 2021).

Viglizzo et al. (2003) do not find a conclusive answer about the sustainability conditions of agricultural systems in the Pampean region and their productive trajectories over time. However, they propose developing a long-term monitoring system of the rural environment based on reliable indicators that serves as a tool to guide environmental policies, promote research priorities and guide communication strategies. In order to implement Viglizzo's approach (2003) and for the regional-scale analysis proposed by this study, the work hypothesis holds that the NDVI seasonal variation curve constitutes not only an appropriate indicator to evaluate the crops productivity, but also to recognize land-use changes that have occurred in the agricultural dry region of Córdoba over time.

In an attempt to assess the dynamics of land-use in the rain-fed region in the province of Córdoba, the objective of the work was to analyze, in each department, the temporal variation between 2000 and 2020 of different indexes related to land-use derived from the NDVI seasonal variation curve. This paper proposes the evaluation of indicators that reveal the predominant land-use modality in a transitional territory comprising humid environments, traditionally used as agricultural areas, and regions characterized by increasing aridity and originally used as livestock farms, in an effort to produce basic information about the sustainability conditions of agricultural systems.

## MATERIALS AND METHODS

### 1. Data

In the central region of Argentina, the climate of the province of Córdoba is characterized by a double thermal and hydric transition (De la Casa and Ovando, 2014). While the warm temperate regime in the north of the territory becomes slightly colder towards the south, the availability of water follows a decreasing gradient from east to west (Rodríguez and De la Casa, 1990). Although crop requirements for energy and temperature are usually satisfied during the summer season, the insufficient or untimely water supply is the main factor that limits productive capacity and generates yield gaps in the region (Aramburu Merlos et al.,

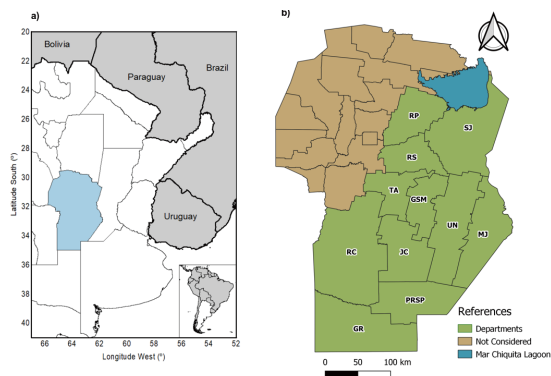
2015), for both corn (De la Casa et al., 2019) and soybean (De la Casa et al., 2018). The study area includes the eleven departments located in the southeast of the province of Córdoba (Figure 1). These departments currently harvest more than 80 % of the provincial production of soybean and corn. Plot sizes exceeding 50 ha of surface cover more than 90 % of the agricultural area in this region (Ghida Daza and Sánchez, 2009).

The soils in this region are classified as entic and typic Haplustolls, and they present a slightly undulating flat relief developed on loessic material, of silt loam texture with a small slope to the east. The climate in the study area is classified as dry sub-humid (Rodríguez and De la Casa, 1990), and the average annual rainfall is approximately 800 mm, concentrated in summer, and shows a decreasing gradient from east to west (Rolla et al., 2018). In this area, agricultural production is mainly rain-fed (Figure 1) and the two predominant summer crops are soybeans and corn (Sayago et al., 2017).

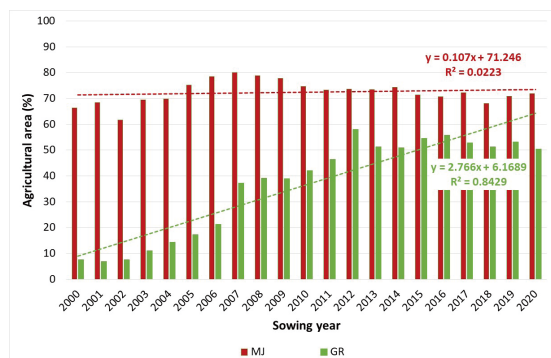
The Ministry of Agriculture, Livestock and Fishery of Argentina (Ministerio de Agricultura, Ganadería y Pesca, MAGyP) provided corn and soybean sowing area data for the eleven most productive rain-fed agricultural departments in Córdoba province (MAGyP, 2021). The information corresponds to the planting area of soybean and corn crops reported each year, which was expressed with respect to the extension of the respective department. Both fractions were accumulated in order to represent the agricultural land area. In order to show the sowing area progress, Figure 2 presents the sowing fraction in the departments of Marcos Juárez and General Roca between 2000 and 2020.

Monthly Normalized Difference Vegetation Index data (MOD13C2) derived from the MODIS sensor on board of the TERRA satellite was used in this study. The MOD13C2 Version 6 product provides a Normalized Difference Vegetation Index (NDVI) value at a per pixel basis in a 0.05-degree latitude/longitude Climate Modeling Grid (CMG). A CMG granule is a geographic grid with 7,200 columns and 3,600 rows representing the entire globe. More details on MODIS NDVI products can be found in Huete et al. (2002).

According to the availability of both crop information and remote sensing data, twenty-one summer crop seasons from September to April of the following year were used (from 2000/2001 to 2020/2021). This product was obtained from the Application for Extracting and Exploring Analysis Ready Samples (AppEEARS) online data system, developed and maintained by NASA GES DISC (Acker and Leptoukh, 2007).



**Figure 1.** a) Location of study area, Córdoba province, Argentina and Argentina location in South America. b) Administrative areas (departments) in Córdoba province. In green departments of rainfed region employed in regional differences analysis. Departments: General Roca (GR), General San Martín (GSM), Juárez Celman (JC), Marcos Juárez (MJ), Presidente Roque Sáenz Peña (PRSP), Río Cuarto (RC), Río Primero (RP), Río Segundo (RS), San Justo (SJ), Tercero Arriba (TA) y Unión (UN).

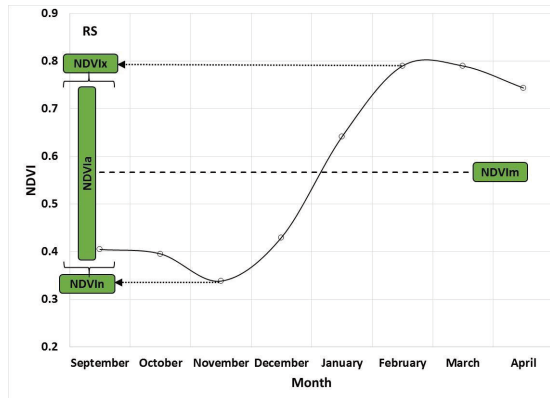


**Figure 2.** Agricultural area (%) in Marcos Juárez (MJ) and General Roca (GR) departments, between 2000 and 2020.

## 2. Methods

Based on the NDVI seasonal variation curve, which considers the potential cultivation period between the months of September and April for each year, as shown in Figure 3. The indicators used for assessing land-use change were:

- The minimum value of NDVI (NDVI<sub>n</sub>): this measure is associated with the sowing operation, followed by crop emergence. The beginning of the phenological curve growth is associated with the “green-up” (first detectable moment of greenness of seasonal plants), which for soybeans is the emergence of crop (Diao, 2020);
- The NDVI maximum value (NDVI<sub>x</sub>): it is associated with the crop potential productivity (Liu et al., 2020);



**Figure 3.** Indicators used to assess land-use changes derived from the NDVI seasonal variation curve. Maximum (NDVI<sub>x</sub>), minimum (NDVI<sub>In</sub>), amplitude (NDVI<sub>a</sub>) and mean (NDVI<sub>Im</sub>) NDVI values.

- The seasonal amplitude NDVI value (NDVI<sub>a</sub> = NDVI<sub>x</sub>-NDVI<sub>In</sub>): it serves to differentiate areas dedicated to livestock where pastures and natural vegetation predominate (platykurtic type curves), with respect to the surface with agricultural use (leptokurtic curves) (Wardlow and Egbert, 2008);
- The mean value of NDVI (NDVI<sub>Im</sub>): it was calculated to express the potential cropping period.

An analysis of the trend of agricultural area and NDVI indicators was conducted. The percentage of sowing in each department, as well as the set of land-use indicators, were analyzed both spatially and temporally. Initially, sectors where changes in land-use were most noticeable were assessed. Subsequently, temporal variations were evaluated based on the change trend over time (2000 to 2020). The linear relationship of each indicator was utilized to determine the slope (positive or negative) as an expression of the temporal change that occurred and its statistical significance. This approach allowed to identify the departments that truly demonstrated effective change.

## RESULTS AND DISCUSSION

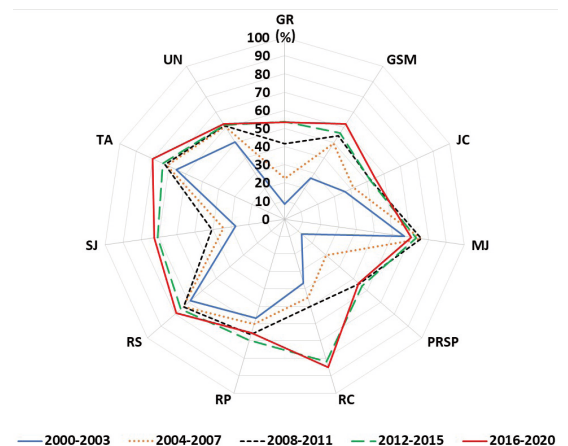
### 1. Expansion of agricultural activity in the region between 2000 and 2020

The information from the 2018 National Agricultural Census (Censo Nacional Agropecuario, CNA-18, 2018), with respect to 2002 (CNA-02, 2002) indicates that livestock production in Argentina experienced a marked decline from 2002 to 2018. The number of farms dedicated to cattle ranching

decreased from 193,886 in 2002 to 130,803 in 2018, representing a reduction of approximately one third (-32.5 %). Likewise, while in the 2002 census the number of bovine cattle was 48,539,411, in 2018 the cattle population amounted to 40,411,905, which represented a 17 % decrease in cattle stock. Although in the Pampas region, which has 71 % of Argentinian livestock, the reduction was 21 %, the decrease in the province of Córdoba was even more pronounced and reached 41 %.

This information reveals that agricultural activity in the dryland region of Córdoba underwent a profound change during the first decades of the 21st century, and that many lands dedicated to cattle ranching migrated over time to agricultural production (Paruelo et al., 2005). The progressive incorporation of agricultural activity in areas originally ranching is evidenced in Figure 4, which shows the increase experienced by the agricultural area with summer crops in each department in the region (only the area occupied with soybeans and corn is considered). Data are presented as four-year averages to reduce the influence of different short-term contingencies (prices, markets, etc.) on sowing decisions.

Figure 4 also indicates that the agricultural area in all sectors corresponds to a smaller departmental fraction at the beginning of the analyzed period (2000-2003), with the agricultural area notably increasing over time. Assuming that the slope of the linear relationship between the sowing area and time represents the rate of agricultural land-use incorporation of each territory, Table 1 shows the trend only in Marcos Juárez (MJ) is not significant,



**Figure 4.** Average cultivated area of corn or soybeans (%) (agricultural land) in major rain-fed agricultural departments of Córdoba province, Argentina, during 2000-2003, 2004-2007, 2008-2011, 2012-2015 and 2016-2020 periods.



although positive as in the rest of the departments.

It is also noteworthy that the increase in the planting area was not uniform across all the region. The difference between the planting fraction in each department in the last period analyzed (2016-2020) and the initial period reached maximum values in the departments of Río Cuarto (RC) (48 %), General Roca (GR) (45 %), San Justo (SJ) (45 %) and Presidente Roque Sáenz Peña (PRSP) (41 %), while it presented minimum values in MJ (4 %); Río Primero (RP) (8 %), Río Segundo (RS) (10 %) and Unión (UN) (12 %), with a particularly notable increase from the period 2008-2011. In this way, it is interpreted that the adoption of agricultural activity originated in the center and SE of the region, where agricultural activity was already established at the beginning of the 21st century, and spread towards the S, SW and N where there was a more prevalent livestock use in the productive systems.

Figure 2 shows two contrasting situations in the change of agricultural land use over the analyzed period (2000-2020); the selected departments were MJ and GR. The agricultural area of MJ remained around 70 % between 2000 and 2020, while GR experienced a significant increase, rising from 10 % at the beginning to 50 % from 2012 to 2020.

The summer production in the region encompasses not only soybean and corn crops but also other species such as peanuts, sorghum, and sunflower, which are regular parts of the rotation. Despite this diversity, the agricultural area dedicated to the study crops during the period 2016-2020 consistently remained above 50 % in all departments, with some areas even reaching 80 % of the total territory.

Therefore, it can be deduced that the seasonal curves of NDVI correspond to and currently represent a predominant agricultural use in the territory of Córdoba. On the other hand, the expansion of agriculture in Córdoba found support, among various technical, economic and commercial factors, due to the fact the climatic conditions were favorable for rain-fed agricultural

practice, sustained by a more humid regime at least until 2010 (De la Casa and Ovando, 2014).

### 2.1 NDVI seasonal variation

Figure 5 presents the NDVI data from September to April, corresponding to the potential growing season of corn and soybeans in the various departments of the region. It also displays the monthly average values for four-year periods, alongside the average value of the complete period (2000-2020), to represent the orderly temporal succession of NDVI in each sector.

The seasonal variation of NDVI in the region presents a unimodal behavior, with minimum values in winter-spring and maximum values in the summer period. Chang et al. (2007) show that the seasonal variation of the NDVI of corn or soybean presents a more abrupt peak (leptokurtic type curve) when the cultivation area is greater than 50 % of the territory and they use the phenological information to discriminate between different environments and agricultural management. This temporal pattern is eventually modified when the production system incorporates double cropping, with a wheat-soybean or wheat-corn sequence, in such a way that the NDVI curve presents two relative maximums (Wardlow and Egbert, 2008). While the first spring maximum in Córdoba is barely perceptible because the wheat area is scarce in the region (De la Casa and Ovando, 2007), the second summer-autumn maximum is more pronounced and the only one the curves show for the spatial resolution of the images used in this work.

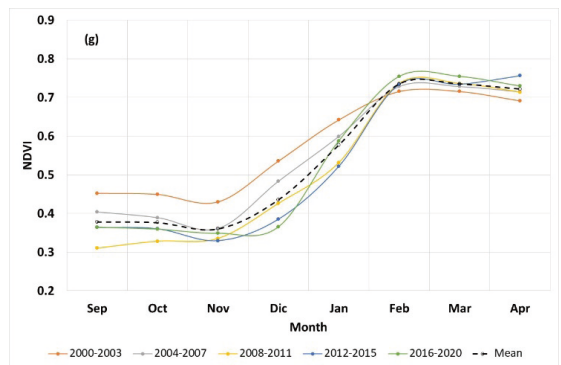
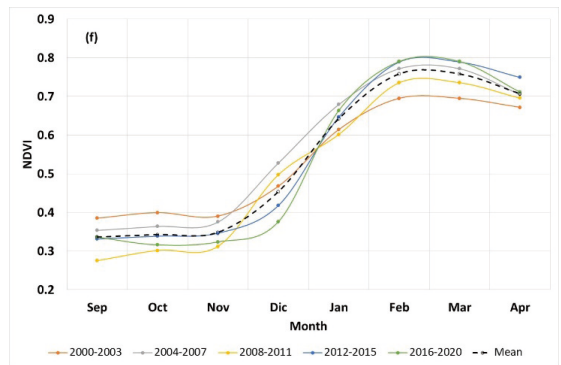
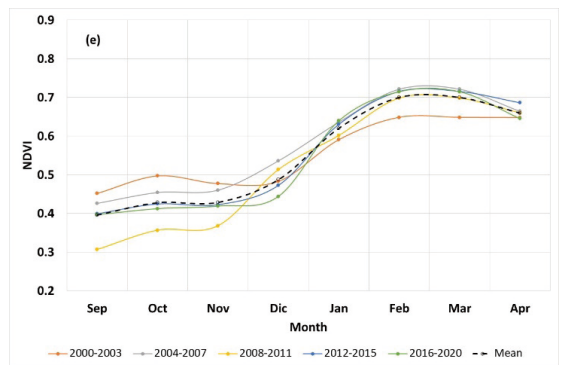
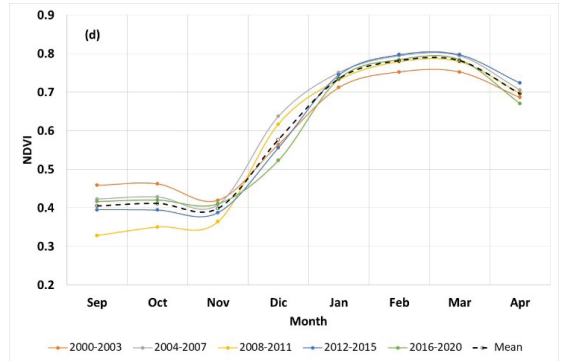
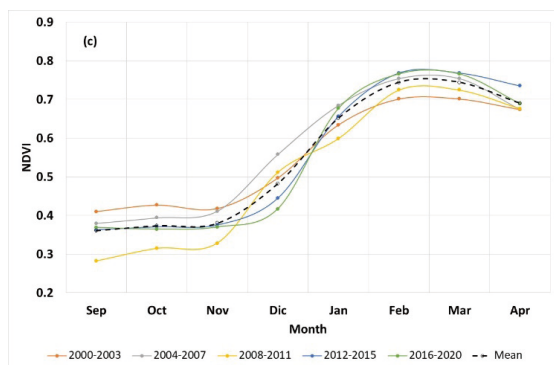
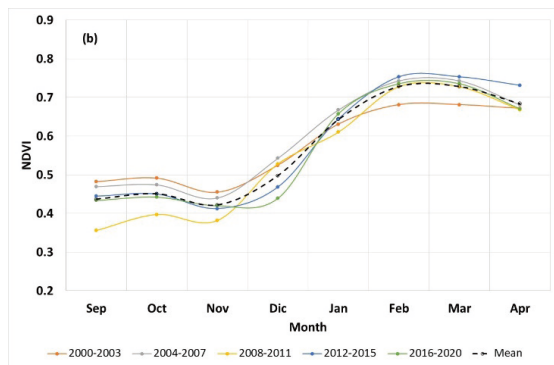
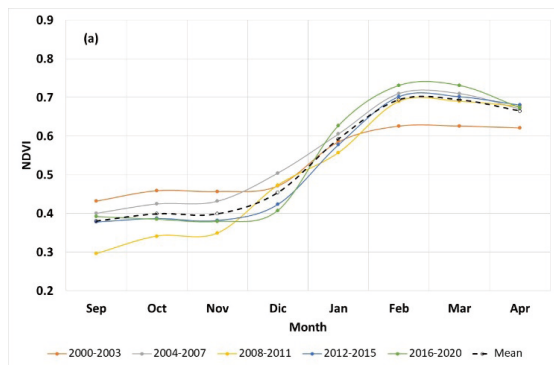
The greater agricultural potential during summer is explained in climatic terms because the rains occur mainly (nearly 80 % of the annual value) during the warm semester (De la Casa, Ovando and Díaz, 2019), so that both water and energy are available resources that contribute to crop growth. The water and heat conjunction is propitious for the rain-fed agricultural production of Córdoba during the warm semester and it also strengthens the dominant role of corn and soybean crops, to the extent that the frequency of extreme yield gaps

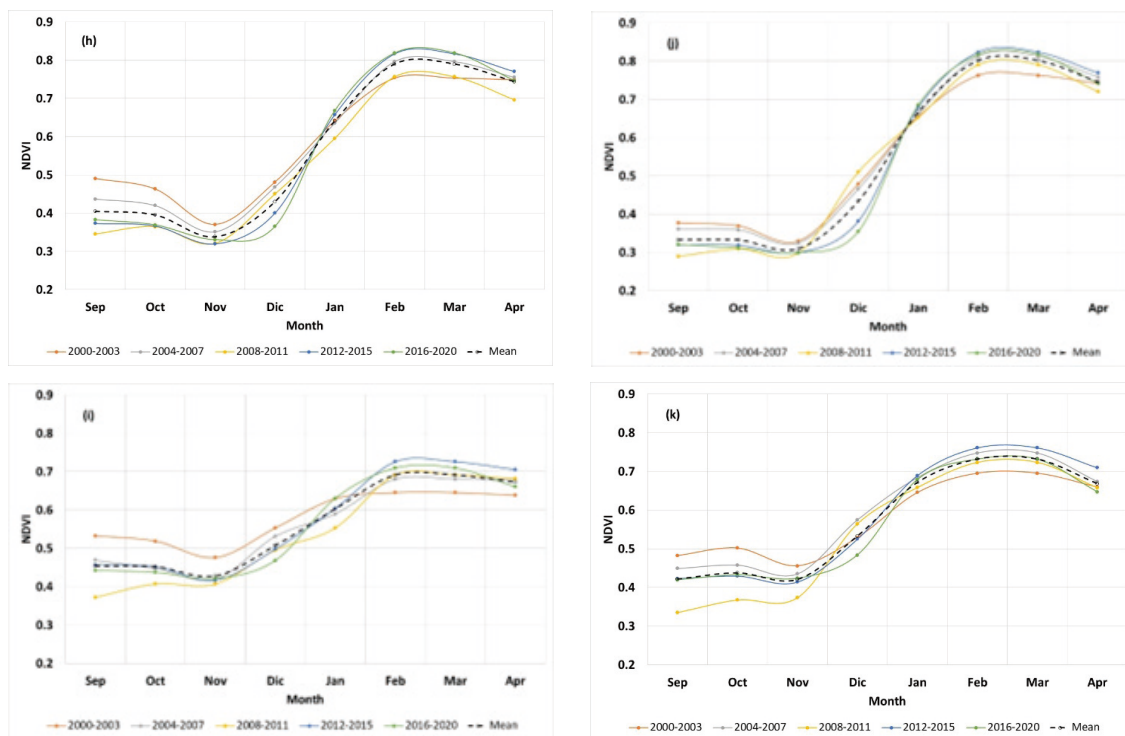
**Table 1.** Regression coefficients (a: intercept; b: slope) of the linear relationship between the departmental fraction planted (agricultural area) and time (years), t value of the slope and its probability (p) for each department in the dryland region of Córdoba, Argentina. The p values <0.05 are significant (in red). Departments: General Roca (GR), General San Martín (GSM), Juárez Celman (JC), Marcos Juárez (MJ), Presidente Roque Sáenz Peña (PRSP), Río Cuarto (RC), Río Primero (RP), Río Segundo (RS), San Justo (SJ), Tercero Arriba (TA) y Unión (UN).

	GR	GSM	JC	MJ	PRSP	RC	RP	RS	SJ	TA	UN
a	-55.231	-37.349	-22.453	-1.426	-48.210	-62.112	-9.571	-10.805	-59.581	-14.498	-10.905
b	0.028	0.019	0.011	0.001	0.024	0.031	0.005	0.006	0.030	0.008	0.006
t	10.095	7.985	5.951	0.659	6.368	11.047	2.670	4.702	11.443	9.137	4.201
p	4.52E-09	1.72E-07	9.97E-06	5.18E-01	4.14E-06	1.03E-09	1.51E-02	1.55E-04	5.75E-10	2.21E-08	4.84E-04

is relatively low for both crops (De la Casa et al., 2018; De la Casa et al., 2019).

Some particular features of the temporal dynamics of the NDVI curve are detected in Figure 5. From the minimum values (NDVI<sub>in</sub>) in winter-spring, associated with the sowing time of the summer crops, the NDVI later on exhibits a vigorous increase that expresses the exponential growth of the crops during the vegetative stage, until reaching a maximum value (NDVI<sub>x</sub>) during the summer. Finally, the NDVI tends to decrease towards the beginning of autumn, when the crops undergo senescence through the final stages of





**Figure 5.** NDVI variation during the summer growing season in the different departments [(a): GR; (b): GSM; (c): JC; (d) MJ; (e): PRSP (f): RC; (g): RP; (h): RS; (i): RJ; (j): TA and (k): UN] of the dryland agricultural region of Córdoba province, Argentina. In addition to the general mean value, those corresponding to 2000-2003, 2004-2007, 2008-2011, 2012-2015 and 2016-2020 periods are presented.

the cycle until their complete physiological maturity and eventually harvest (Seo et al., 2019).

In addition to this generalized seasonal fluctuation in the region, a common temporal pattern is also observed. Taking into account the general average value of each department as a reference, an interesting trend emerges: during the initial 4-year period, NDVI values at the time of planting consistently exceeded the average, while the maximum (peak greenness) values during this period consistently fell below. Conversely, this pattern has reversed in the most recent periods, with minimum values consistently recorded below the long-term average and maximum values surpassing it (Figure 5).

This behavior denotes an increase in amplitude (NDVIa) as time elapses from the first cycles to the present. In this sense, an increase in the amplitude of the seasonal variation curve of the NDVI is interpreted as associated with a progressive adoption of agricultural activity, particularly in those departments that at the beginning of the 21st century predominantly had livestock use.

## 2.2 NDVI trend assessment

The aspects described about Figure 5 were analyzed objectively, considering the trend experienced by the NDVI monthly values in each sector over the 21-year period. This information is presented graphically in Figure 6, which shows in particular the information from GR and MJ, while in Table 2 the evaluation extends to the entire region.

In correspondence with Figure 2, it can be seen that the change in NDVI over time has been more generalized in GR, since in four of the eight months the time trend is significant. On the other hand, while in October, November and December the slopes are negative, the condition is reversed in February. Only December shows a significant NDVI decrease in MJ, while the changes (increase or decrease) for the rest of the months are barely perceptible and accidental.

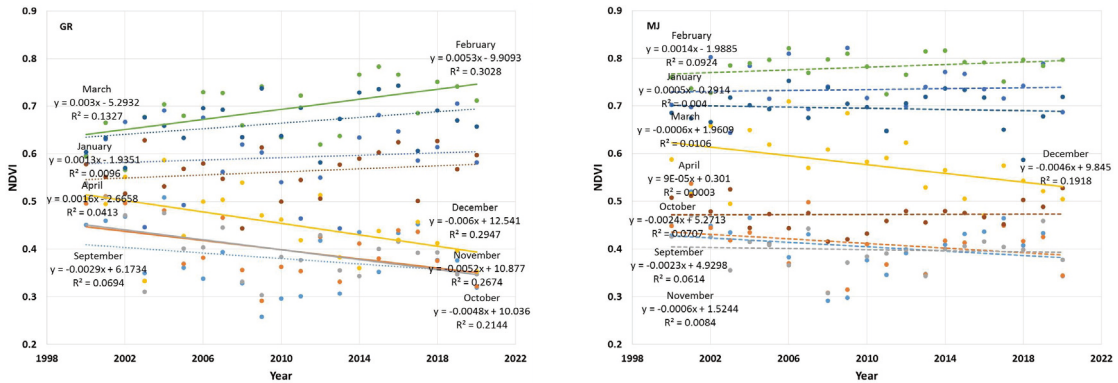
From Table 2, the NDVI value between September and December shows a tendency to decrease in the twenty-one years analyzed. The rates are negative in all the departments considered and reach a significant condition ( $p < 0.05$ ) mainly in November and December. On the contrary, between January



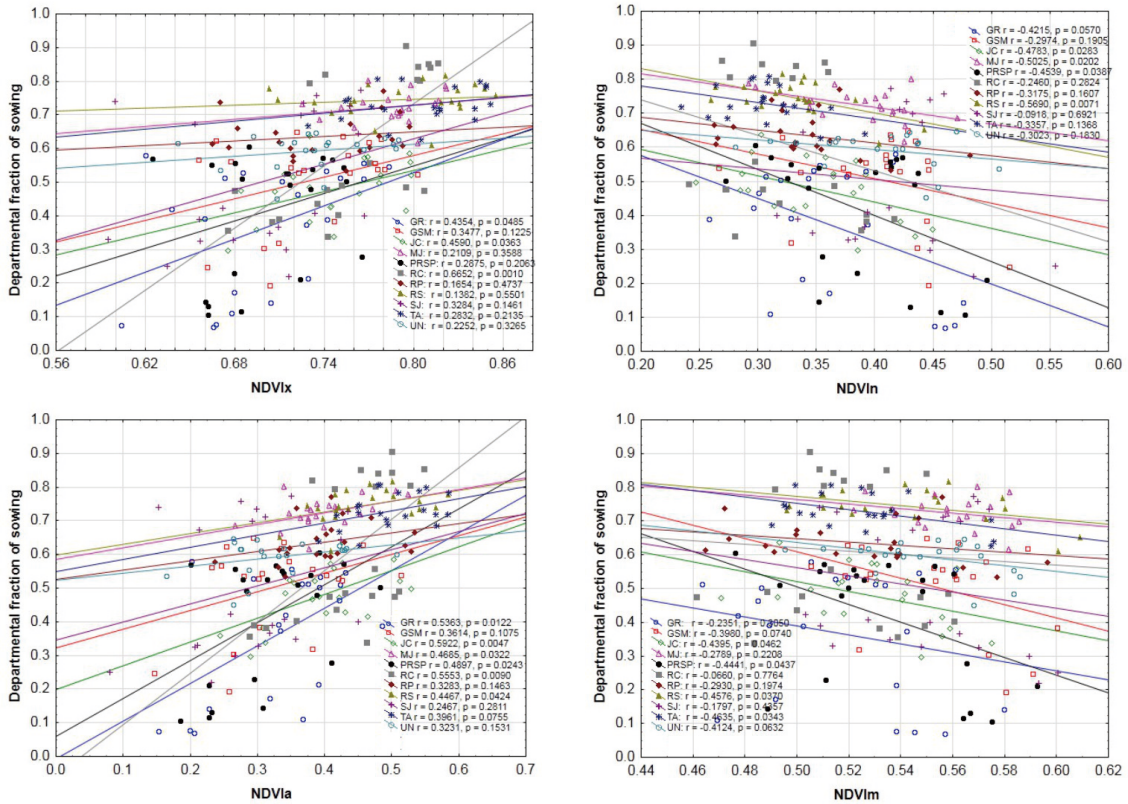
**Table 2.** Interception (a), slope (b), t value and probability (p) of the linear relationship (trend) between the NDVI monthly values (dependent variable) and time (years between 2000 and 2020) in the departments of the dryland agricultural region of Córdoba, Argentina.

Department	a	b	t	p	a	b	t	p
	September				January			
GR	6.173	-0.003	-1.190	0.249	-1.935	0.001	0.430	0.672
GSM	6.240	-0.003	-1.152	0.264	-0.040	0.000	0.140	0.890
JC	5.013	-0.002	-1.094	0.288	-1.709	0.001	0.479	0.638
MJ	4.930	-0.002	-1.115	0.279	-0.291	0.001	0.276	0.786
PRSP	7.328	-0.003	-1.441	0.166	-2.994	0.002	0.681	0.504
RC	6.682	-0.003	-1.792	0.089	-2.067	0.001	0.593	0.560
RP	9.461	-0.005	-1.807	0.087	9.908	-0.005	-1.650	0.115
RS	13.169	-0.006	-2.903	0.009	-1.440	0.001	0.346	0.733
SJ	8.604	-0.004	-1.564	0.134	0.587	0.000	0.003	0.998
TA	7.703	-0.004	-2.476	0.023	-2.018	0.001	0.576	0.572
UN	7.261	-0.003	-1.470	0.158	-1.907	0.001	0.565	0.579
	October				February			
GR	10.036	-0.005	-2.277	0.035	-9.909	0.005	2.872	0.010
GSM	6.477	-0.003	-1.168	0.257	-4.471	0.003	1.627	0.120
JC	7.585	-0.004	-1.848	0.080	-6.444	0.004	2.905	0.009
MJ	5.271	-0.002	-1.203	0.244	-1.989	0.001	1.391	0.180
PRSP	10.481	-0.005	-2.190	0.041	-5.653	0.003	2.258	0.036
RC	10.200	-0.005	-2.978	0.008	-9.428	0.005	3.605	0.002
RP	9.755	-0.005	-1.943	0.067	-3.773	0.002	1.576	0.132
RS	11.778	-0.006	-2.553	0.019	-5.873	0.003	2.055	0.054
SJ	7.603	-0.004	-1.278	0.217	-7.198	0.004	1.948	0.066
TA	7.913	-0.004	-2.361	0.029	-4.516	0.003	2.003	0.060
UN	8.089	-0.004	-1.598	0.127	-2.910	0.002	1.304	0.208
	November				March			
GR	10.877	-0.005	-2.634	0.016	-5.293	0.003	1.705	0.104
GSM	5.354	-0.002	-1.246	0.228	-1.372	0.001	0.639	0.531
JC	6.852	-0.003	-2.009	0.059	-3.817	0.002	1.523	0.144
MJ	1.524	-0.001	-0.402	0.692	1.961	-0.001	-0.451	0.657
PRSP	8.438	-0.004	-2.071	0.052	-0.285	0.000	0.335	0.741
RC	8.650	-0.004	-2.772	0.012	-5.572	0.003	1.775	0.092
RP	9.805	-0.005	-2.671	0.015	-5.440	0.003	1.842	0.081
RS	6.029	-0.003	-1.820	0.085	-0.046	0.000	0.217	0.830
SJ	6.472	-0.003	-1.659	0.114	-2.725	0.002	1.038	0.312
TA	4.654	-0.002	-1.852	0.080	0.162	0.000	0.186	0.855
UN	4.405	-0.002	-1.146	0.266	0.447	0.000	0.082	0.936
	December				April			
GR	12.541	-0.006	-2.818	0.011	-2.666	0.002	0.904	0.377
GSM	14.144	-0.007	-3.666	0.002	1.295	0.000	-0.183	0.857
JC	15.292	-0.007	-3.443	0.003	-2.328	0.001	0.700	0.493
MJ	9.845	-0.005	-2.124	0.047	0.301	0.000	0.073	0.943
PRSP	9.585	-0.005	-2.328	0.031	2.207	-0.001	-0.491	0.629
RC	16.434	-0.008	-3.883	0.001	-1.272	0.001	0.431	0.671
RP	22.596	-0.011	-6.473	0.000	-5.779	0.003	1.620	0.122
RS	17.300	-0.008	-4.058	0.001	3.867	-0.002	-0.676	0.507
SJ	11.729	-0.006	-2.847	0.010	4.589	-0.002	-1.461	0.160
TA	19.203	-0.009	-3.929	0.001	2.394	-0.001	-0.350	0.730
UN	8.995	-0.004	-2.226	0.038	2.685	-0.001	-0.685	0.502

References: In red (orange) the significant slopes at 5 % (10 %).



**Figure 6.** Variation and trend of NDVI in General Roca (GR) and Marcos Juárez (MJ) for each month of summer crops growing cycle between September and April. In a continuous line (with dashes) and label to the right (left) the significant cases ( $p < 0.05$ ) (not significant).



**Figure 7.** Relationship between the departmental fraction of sowing and different spectral indicators derived from the Normalized Difference Vegetation Index (NDVI): maximum (NDVI<sub>x</sub>), minimum (NDVI<sub>in</sub>), amplitude (NDVI<sub>a</sub>) and mean (NDVI<sub>m</sub>) in different departments of the rain-fed region of Córdoba province, Argentina.

and April the NDVI values tend to increase, at least in those cases where the trend is significant. While NDVI values between September and December in the first years of the analysis are higher than the most recent ones, February and March show the opposite behavior, with values that are currently higher.

The decreasing rate of NDVI recorded in the region during the first half of the crop growing season is interpreted by a gradual change in soil use which in the first years presented a more widespread cattle practice and a greater proportion of land occupied with pastures –especially in the western and southern sectors– but later gradually shifted to agricultural practices. While the changes

in the departments of MJ, UN and GSM are less evident, since only in December the negative trend is significant, in the rest of the departments they are more pronounced and expose the increase in agricultural land-use in the region. This would also explain the NDVI increase during February and March with respect to the values at the beginning of the series, giving rise to a seasonal curve whose amplitude is more pronounced, which is typical of land-use where agricultural activity predominates (De la Casa and Ovando, 2007; Wardlow and Egbert, 2008). In addition to the more extended agricultural use, the tendency of the NDVI to decrease in December is also explained by the fact that delaying the sowing date of summer crops is beginning to be adopted as a common practice in the region (De la Casa et al., 2019).

### 3. Spectral indicators of land-use

In order to evaluate land-use change, mainly associated with the increase in agricultural activity, the linear relationship between the planting area of summer crops and different spectral indicators derived from the NDVI signal was established. Agricultural use is associated with the sown area in the departments and only considers soybean and corn crops, which are widely spread in the region. Since there are also other summer planting crops, the magnitude of the fraction is considered to represent a base value. Figure 7 shows the information obtained for each department of the rain-fed region of Córdoba.

For the entire region as a whole, the linear relationships of the annual sown area with respect to NDVI<sub>x</sub>, NDVI<sub>n</sub> and NDVI<sub>a</sub> show correlation coefficients of 0.596, -0.360 and 0.559, respectively. Although moderate, all coefficients are significant ( $p < 0.001$ ), which evidences the increase in planting area. Consequently, the land-use for agricultural activity is linked both directly with respect to the maximum value as inversely to the minimum of the NDVI seasonal curve. As both expressions in conjunction determine the amplitude of the NDVI seasonal curve, which is positively related also to the sown area, the increase in NDVI<sub>a</sub> is concurrent with the increase in the planting area and agricultural land-use. This relationship with respect to NDVI<sub>a</sub> also reaches significance ( $p < 0.05$ ) in six (GR, Juárez Celman (JC), MJ, PRSP, RC and RS) of the eleven departments that make up the region under study. Beyond the intensity of the signal, the slopes of the relationships also allow us to recognize that while the soybean and corn sowing area in some departments shows a relatively minor change

throughout the period studied, in other sectors the increase has been particularly noticeable. On the other hand, the observed dispersion is justified to the extent that the planting decision is prior to the development that the seasonal NDVI curves actually reach, subject to particular climatic conditions during the cycle, which influence both NDVI<sub>x</sub>, NDVI<sub>n</sub> and NDVI<sub>a</sub> values.

Furthermore, Figure 7 shows inverse relationships between NDVI<sub>m</sub> and agricultural areas in all sectors. Although the correlation is not significant for the complete data set ( $-0.092$ ;  $p = 0.16$ ), linear relationships are significant ( $p < 0.05$ ) in the departments of JC, PRSP, RS, and TA. As a preliminary explanation, it can be

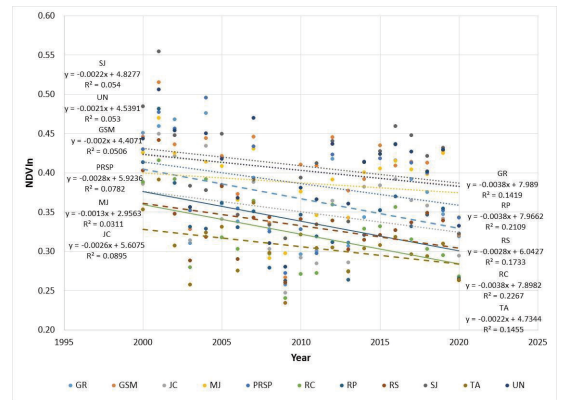


Figure 8. Minimum NDVI value (NDVI<sub>n</sub>) variation over time and analysis of its linear trend in the different departments of the dryland region of Córdoba province, Argentina. Solid line indicates a significant slope at 5 %, dashed line indicates significant at 10 % (on the right) and dotted line indicates not significant (on the left).

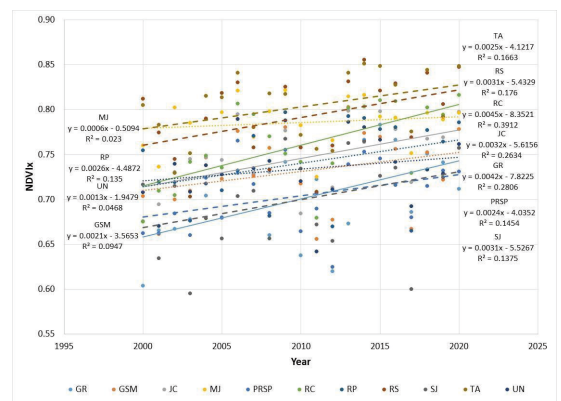


Figure 9. Maximum NDVI value (NDVI<sub>x</sub>) variation over time and analysis of its linear trend in the different departments of the dryland agricultural region of Córdoba province, Argentina. The solid line and the dashed line indicate a significant slope at the 5 % and 10 % levels, respectively (on the right), while the dotted line is not significant (on the left).

interpreted that the larger agricultural area would be associated with a slight decrease in the mean NDVI value, probably because agricultural systems have a lower capacity to fix carbon compared to livestock systems.

Kumar Oad et al. (2020) used Land Surface Temperature (LST) records instead of NDVI, to analyze changes in rice planting and harvest dates. They determined a significant linear relationship between rice production area and LST, and pointed out that higher vegetative growth in the region is associated with lower LST values. In the same sense and according to the negative correlation that exists between LST and NDVI (Sun and Kafatos, 2007; Johnson, 2014; Ullah et al., 2020), the results obtained from the NDVI can be considered indicative of the agricultural land-use in the dryland region of Córdoba.

#### 4. Temporal variation (trend) of land-use indicators

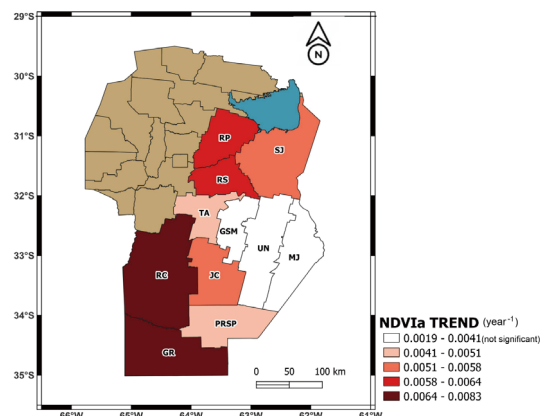
Once the relationships between NDVI<sub>x</sub>, NDVI<sub>n</sub>, NDVI<sub>a</sub> and NDVI<sub>m</sub> with the planted area were evidenced, the temporal change of these spectral indicators related in a broad sense to both practice and agricultural use is analyzed below.

##### 4.1 Trend of NDVI minimum values

The NDVI<sub>n</sub> variation over time is presented in Figure 8. Throughout the region, NDVI<sub>n</sub> shows a systematic decrease, although the trend only reaches a significant character ( $p < 0.05$ ) in the departments of RC and RP and, with less certainty ( $p < 0.10$ ), also in GR, RS and Tercero Arriba (TA). Until 2009, when an episode of La Niña accompanied the considerable decrease in rainfall events in the region (De la Casa, Ovando and Díaz, 2019), the decrease in NDVI<sub>n</sub> is ostensible but, subsequently, a more stable value is evident. Without discarding the long-term change NDVI<sub>n</sub> presents between 2000 to 2020, the periodic behavior of the series is also recognized. This variation is in correspondence to the fluctuating nature of rainfall in the region, with cycles of ten and twenty years of duration (De la Casa and Nasello, 2010) and a breaking point around 2009, so that the decreasing rate until then acquires a positive trend.

##### 4.2 Trend of NDVI maximum values

The change over time of NDVI<sub>x</sub> is shown in Figure 9. Throughout the region, NDVI<sub>x</sub> shows a systematic upward trend, with rates of a significant nature ( $p < 0.05$ ) in the departments of GR, JC and



**Figure 10.** Temporal trend of NDVI amplitude (NDVI<sub>a</sub>) from 2000 to 2020 in the departments of the dryland agricultural region of Córdoba, Argentina. Departments: General Roca (GR), General San Martín (GSM), Juárez Celman (JC), Marcos Juárez (MJ), Presidente Roque Sáenz Peña (PRSP), Río Cuarto (RC), Río Primero (RP), Río Segundo (RS), San Justo (SJ), Tercero Arriba (TA) y Unión (UN).

RC and, with less certainty ( $p < 0.10$ ), also in PRSP, RS, SJ and TA.

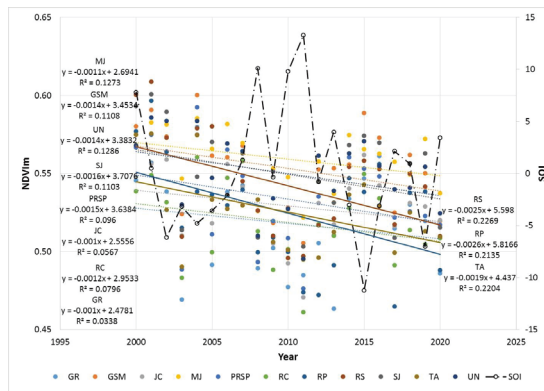
While dryland agriculture in Córdoba in the core zone (MJ, UN, GSM) does not present a relevant change in NDVI<sub>x</sub> over time, the peripheral region where agricultural activity has expanded presents a significant growth peak increase. In addition to the gradual increase in agricultural land-use, the positive trend of NDVI<sub>x</sub> reveals, based on its positive relationship with crop productivity (Becker-Reshef et al., 2010; Bolton and Friedl, 2013; Liu et al., 2020), that the increase in agricultural area in marginal territories, beyond accidental fluctuations, found favorable conditions.

##### 4.3 Trend of NDVI amplitude values

The decrease in NDVI<sub>n</sub> and the increase in NDVI<sub>x</sub> together imply an increase in the amplitude (NDVI<sub>a</sub>) of the seasonal variation of the NDVI curve, a typical condition of a productive system where agriculture constitutes the predominant activity in the territory. An objective evaluation of the NDVI<sub>a</sub> variation from 2000 to 2020 was made from the trend analysis, as shown in Figure 10. Unlike Figures 8 and 9, the map in Figure 10 presents the information on the trend of NDVI<sub>a</sub> values in a territorial way, to highlight those departments where the changes are significant and recognize the sectors that do not reach this condition.

The NDVI amplitude trend is increasing throughout the region, as shown in Figure 10, and only in MJ, UN and GSM the linear slope is not significant, highlighting that the change is





**Figure 11.** NDVI mean value (NDVI<sub>m</sub>) from 2000 to 2020 and the linear trend in the departments of the dryland agricultural region of Córdoba, Argentina. The solid line and the dashed line indicate a significant slope at the 5 % and 10 % levels, respectively (on the right), while the dotted line is not significant (on the left). Superimposed on the graph is the line that represents the annual values of the Southern Oscillation Index (SOI), indicating the state of the ENSO phenomenon. Departments: General Roca (GR), General San Martín (GSM), Juárez Celman (JC), Marcos Juárez (MJ), Presidente Roque Sáenz Peña (PRSP), Río Cuarto (RC), Río Primero (RP), Río Segundo (RS), San Justo (SJ), Tercero Arriba (TA), y Unión (UN).

less evident in the core zone, where agriculture was already established in 2000. On the other hand, in the rest of the departments of the dryland agricultural territory of Córdoba the increase rate of NDVI<sub>a</sub> is significant ( $p < 0.05$ ). Although with a slightly lower level of security in PRSP ( $p < 0.10$ ) and in SJ ( $p < 0.107$ ), this situation shows the agricultural land-use intensification is located particularly in those marginal areas. Although agricultural land-use increase is present throughout the region, to the extent that the NDVI seasonal variation curves show a greater difference between NDVI<sub>x</sub> and NDVI<sub>n</sub>, the change is less noticeable in those traditional agricultural sectors of the southeast and center. Instead, in the southern and western areas of the region, where the greatest incorporation of soils for agricultural activity occurred in the last twenty years, this signal is more noticeable.

#### 4.4 Trend of NDVI mean values

Another aspect to highlight of the NDVI seasonal curve results from taking the average (NDVI<sub>m</sub>) or its integral during the potential crop growing period. Figure 11 shows the temporal variation of NDVI<sub>m</sub> in the different sectors of the agricultural region under study.

The NDVI<sub>m</sub> value registers the general downward trend in the region, although the negative slope is significant ( $p < 0.05$ ) only in RP, RS and TA. However, and although the linear model is relevant to determine the long-term decrease in NDVI<sub>m</sub>,

the Figure 11 allows to recognize the fluctuating behavior of NDVI<sub>m</sub> also extended throughout the study area. At the beginning of the analyzed period, NDVI<sub>m</sub> presents high values, associated with NDVI<sub>n</sub>, which were also high during those years. Then, a marked decrease in NDVI<sub>m</sub> between 2008 and 2011 is explained by the impact of unusually dry years, under an intense and prolonged La Niña episode (De la Casa et al., 2019), and a strong increase subsequently under El Niño during 2015-2016 (the South Oscillation Index [SOI] value was added in Figure 11 to point out the El Niño-South Oscillation [ENSO] status each year). In this way, although the trend of NDVI<sub>m</sub> in all departments is decreasing and for some of them even significantly in terms of statistics, a certain periodic behavior linked to the close dependency between growth and state of the crops is recognized, as represented by the NDVI, and fluctuations in the weather conditions.

In this marginal region of Córdoba where agriculture has been recently established as the main productive activity, the underlying question is about the sustainability of the change in land-use through time. If the NDVI<sub>m</sub> value is taken as an indicator of the productive capacity, the gradual decrease throughout the period studied would be exposing some reduction in its potential, subordinated to the lack of sustainability of the region to maintain agricultural production capacity, or to climatic conditions have been degrading over time. Nor can it be ruled out that agricultural production systems have a lower capacity to fix carbon compared to traditional livestock systems based on pasture feeding.

## CONCLUSIONS

The rain-fed production region of Córdoba experienced an intensification of agricultural land-use between 2000 and 2020, so that the planting area of summer crops (soybean and corn crops only) in each department currently exceeds 50 % of its territory. In addition to the information available in censuses and productive statistics, this change is revealed by considering different expressions derived from the NDVI seasonal variation curve: the maximum value (NDVI<sub>x</sub>), the minimum (NDVI<sub>n</sub>) and the amplitude (NDVI<sub>a</sub>). The evidence analyzed shows that NDVI<sub>a</sub> is directly related to the joint planting area of soybean and corn and, consequently, it is indicative of the agricultural use of the territory.

The analysis of the NDVI seasonal curves through time reveals substantial changes in agricultural



activity in the dryland region of Córdoba. While the intensification of the agricultural use of the territory is evident by the decrease in NDVI<sub>n</sub>, the increase in NDVI<sub>x</sub> and the general increasing trend of the NDVI<sub>a</sub>, these changes are particularly evident in those departments where agricultural activity increased the area in a greater proportion. Thus, in the departments of MJ, UN and GSM, which constitute the core area of agriculture in the region and where the increase in agricultural area has been less, the slope of NDVI<sub>a</sub>, although positive, does not reach statistical significance ( $p < 0.05$ ). On the contrary, the marginal departments (GR, PRSP, RC, SJ) that in the last twenty years have increased their agricultural area in a sustained way, exhibit a significant positive trend in the NDVI<sub>a</sub> value.

The NDVI<sub>x</sub> or peak of greenness has increased its value in a general way, although with a significant character, mainly in the peripheral areas of the region. As an indicator directly linked to agricultural productivity, it constitutes evidence in favor of the fact that the incorporation of agricultural activity did not have a negative impact on productive capacity.

On the contrary, the negative trend of NDVI<sub>m</sub> extended throughout the territory constitutes an alert signal about the sustainability of agricultural production systems in the region, mainly in the RP, RS and TA sectors where the slope is significant. The progressive decrease in NDVI<sub>m</sub> could be attributed to the fact that current conditions are less conducive to sustaining initial productivity, an aspect that would be linked to the deterioration caused by agricultural intensification. In another sense, it could be associated with less favorable climatic conditions in recent years, or because the agricultural systems have naturally less capacity to fix carbon than livestock systems based on pastures. Discerning about the possible loss of sustainability or that the climatic conditions are currently less favorable is an aspect that must be assessed in particular.

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