Bragantia
ISSN: 0006-8705
ISSN: 1678-4499
Instituto Agronômico de Campinas

Fontana, Denise Cybis; Junges, Amanda Heemann; Bremm, Carolina; Schaparini, Laura Pigatto; Mengue, Vagner Paz; Wagner, Ana Paula Luz; Carvalho, Paulo

NDVI and meteorological data as indicators of the Pampa biome natural grasslands growth

Bragantia, vol. 77, no. 2, 2018, pp. 1-11
Instituto Agronômico de Campinas

DOI: 10.1590/1678-4499.2017222

DOI: http://dx.doi.org/10.1590/1678-4499.2017222

NDVI and meteorological data as indicators of the Pampa biome natural grasslands growth

Denise Cybis Fontana[1]*, Amanda Heemann Junges[2], Carolina Bremm[2], Laura Pigatto Schaparini[1], Vagner Paz Mengue[3], Ana Paula Luz Wagner[4], Paulo Carvalho[1]

1. Universidade Federal do Rio Grande do Sul - Faculdade de Agronomia - Porto Alegre (RS), Brazil.
2. Fundação Estadual de Pesquisa Agropecuária - Porto Alegre (RS), Brazil.
3. Universidade Federal do Rio Grande do Sul - Centro Estadual de Pesquisas em Sensoriamento Remoto e Meteorologia - Porto Alegre (RS), Brazil.
4. University of Florida - Institute of Food and Agricultural Sciences - Agricultural and Biological Engineering Department - Gainesville (FL), United States.

ABSTRACT: The present study aimed to characterize the dynamics of NDVI and meteorological conditions, relating both to the annual dynamics of biomass accumulation in natural pastures of the Pampa biome as a way of subsidizing growth modeling. Forage accumulation rate data from a long-term experiment, NDVI data from the MODIS images, and meteorological data measured at the surface were used. We verify that the agrometeorological element associated to the accumulation of forage in the natural grasslands is different according to the season, which is typical of the subtropical climate. Winter is the critical season for livestock production due to the lower forage accumulation rate and lower values of NDVI, conditioned by the decrease of solar radiation and air temperature. In the summer, the limiting factor to forage accumulation is the hydric condition. It was also verified that the variability in the growth of grasslands can be associated with the ENSO phenomenon, being the El Niño favorable and the La Niña unfavorable, especially in the spring-summer period. Considering the verified associations, spectral indices combined with agrometeorological elements are recommended to the adjustment of models of forage accumulation in the Pampa biome natural grasslands.

Key words: biomass accumulation, ENSO, MODIS, ground data.

*Corresponding author: dfontana@ufrgs.br

Received: Jul. 5, 2017 – Accepted: Oct. 24, 2017

INTRODUCTION

The exploration of natural grasslands for livestock production is considered an activity of high economic, social and environmental relevance. In the State of Rio Grande do Sul (RS), Brazil, the Pampa biome natural grasslands are the food base of 14.1 million cattle and 4.1 million sheep (IBGE 2017). These grasslands are characterized by a wide floristic diversity (Boldrini 1997) with the spatial and temporal variability of the vegetation growth. As a consequence, the climatic conditions affect the forage productivity and are especially important to livestock production (Overbeck et al. 2007).

In the Pampa biome, the pressure for the change of land use and cover is significant, with area decreasing in annual rates of 410,000 ha only in RS. Besides, there is also degradation and losses of floristic biodiversity resulting from mismanagement actions in livestock production (Pilar and Vélez 2010). Carvalho (2013) pointed out that, considering that the vocation of natural grasslands is animal production, the first step to undertake adequate productive and sustainable policies is to understand the biome, its potentialities and vulnerabilities, its functioning and the ecological interactions of the individuals that coinhabit and coevolve in it over time.

In this sense, it is known that climatic variability influences all types of vegetation growth and, in the Pampa biome, causes variations in the forage availability to the animals throughout the seasons and also years. In RS State, rainy subtropical climate predominates, without the occurrence of a dry season, however with important variation in energy supply throughout the year and highly variability between years. Thus, the vegetation responds to the climatic conditions with differential growth throughout the year and between years. It is also known that RS is located in a region influenced by the El Niño Southern Oscillation (ENSO) phenomenon (Berlato and Fontana 2003), allowing a part of the high interannual meteorological conditions variability to be predicted and, therefore, to be used as guidance to the Pampa biome natural grasslands management.

Studies that improve the understanding of the factors that determine the natural grasslands growth and the forage availability for grazing animals are strategic, both to obtain greater profitability of livestock production and for the establishment of strategies for the sustainable use of the Pampa biome grasslands. Also relevant is the establishment of methodologies capable of characterizing the temporal dynamics and the spatial heterogeneity of vegetation growth, emphasizing the use of information collected by remote orbital sensors in the form of vegetation indices (VI).

The VI are obtained from the recording and processing by mathematical operations the electromagnetic energy, at certain intervals of wavelength (bands), coming from the surface and detected by a remote sensor. Very often the red and the near-infrared bands are used to elaborate VI, given its association with some biophysical parameters of the vegetation (Fonseca et al. 2007) and phenology. Therefore, VI shows potential to obtain inferences about growth and development of the vegetation in general (Soudani et al. 2012). They also have had, in RS, a significant use in monitoring, either for annual agricultural crops (Junges et al. 2013; Santos et al. 2014; Mengue and Fontana 2015), for grasslands (Fonseca et al. 2007; Soudani et al. 2012; Wagner et al. 2013; Scottá and Fonseca 2015; Junges et al. 2016) or forests (Berra et al. 2014).

The data to obtain VI are derived from several sensors, and the choice of sensor type depends fundamentally on the study objectives. When the objective is to generate information of an operational character and regional scope, a sensor that has been highlighted is the MODIS (Moderate Resolution Imaging Spectroradiometer), used in several environmental conditions. The MODIS sensor is aboard two platforms, Acqua and Terra, and it daily obtains images in 36 spectral bands, from which products with different processing levels are generated and distributed free of charge in near real time. The product MOD13Q1, which includes vegetation indices, is one of the most used for monitoring vegetated surfaces due to the spatial and temporal resolutions compatible with the evolution of the main agricultural activities, and not yet available on other sensors.

The hypothesis of this study is that NDVI/MODIS can be used as an indicator of natural grasslands growth, which is associated to the climate conditions and management, and that this information can be useful on the Pampa biome livestock production and sustainability. In this context, the objective of this study was to characterize the dynamics of NDVI and meteorological conditions, relating both to the annual dynamics of biomass accumulation in →

natural pastures of the Pampa biome as a way of subsidizing growth modeling.

MATERIAL AND METHODS

The area of study corresponded to 64 ha of natural grassland at the Agronomic Experimental Station of the UFRGS – Universidade Federal do Rio Grande do Sul – located in Eldorado do Sul, RS (Figure 1). In the experiment, conducted since 1986, different levels of forage allowance are available to cattle throughout the year, which determines that the plots show differences in their floristic composition and in the vegetation growth and development throughout the year and in between years. The adjustment of stocking for maintenance of the recommended forage allowance is carried out by means of the continuous grazing method with variable stocking rate. The experimental animals used were beef heifers from crosses among the Angus, Hereford and Nelore breeds, with a live weight of 244.8 ± 39.0 kg, allocated annually in the experimental units. In the present study, the treatment was evaluated between 2000 and 2013, in which the forage allowance corresponds to approximately 12 kg of dry matter (DM) per 100 kg of live weight (LW) throughout the year (Moderate Supply), which is considered the management that provides the best relation between animal and vegetal production (Carvalho 2013).

The Forage Accumulation Rate (FAR), expressed in kg DM/ha/day, was determined every 28 days using four grazing exclusion cages per experimental unit, according to the methodology by Klingman et al. (1943). Three experimental units were demarcated for the treatment of moderate grazing intensity, using GPS (Global Positioning System), according to the delimitation of three pixels of the MODIS sensor images (250 meters of spatial resolution). NDVI (Normalized Difference Vegetation Index) was obtained from the composition images of maximum value of 16 days of the MODIS sensor, product MOD13Q1, for the period from 2000 to 2013, acquired from NASA (NASA 2016). The processing of transformation, mosaicking and extraction of values from the areas of interest of the images was performed in the Envi 5.2 software.

For the same period, data on global solar radiation (Rs), air temperature (T) and relative air humidity (RH), wind velocity (v) and rainfall (r) from an automatic weather

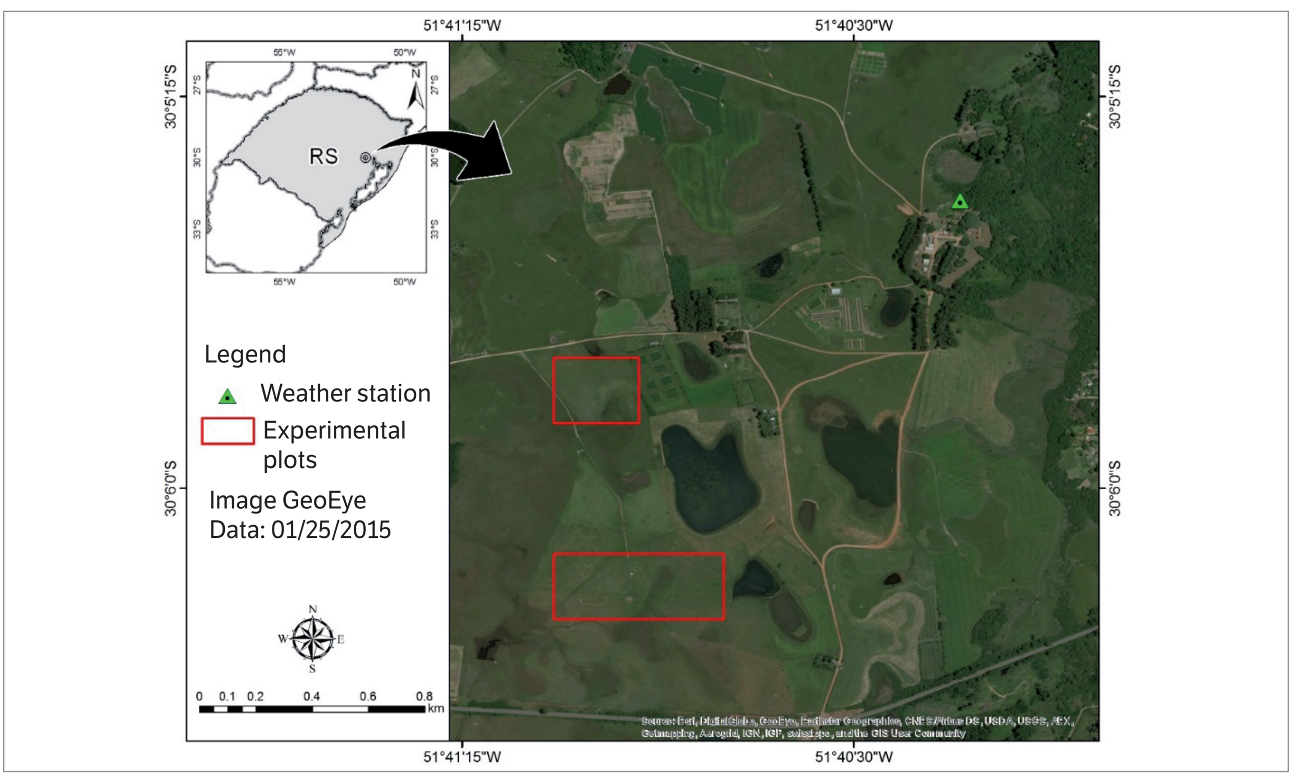

Figure 1. GeoEye image highlighting the studied area (red rectangles) and the weather station (green triangle). Eldorado do Sul, Rio Grande do Sul, Brazil.

station located near the experimental area were used for monitoring the weather conditions (UFRGS 2016). Water deficit and the frost index were also determined.

The water deficit (DEF) was measured through the meteorological water balance (Thornthwaite and Matter 1955), considering the soil water storage capacity (WSC) of 40 mm and the potential evapotranspiration (PET) estimated by the Penman equation (1956).

The frost damage index (FI) was calculated (Eq. 1) based on the frequency of occurrence of ranges of weighted absolute minimum temperatures ($Tabs_{min}$) (Cunha et al. 2005): weight 1: 2 °C > $Tabs_{min}$ > 0 °C; weight 2: 0 °C > $Tabs_{min}$ > −2 °C; and weight 3: $Tabs_{min}$ < −2 °C.

$$Fl = 1\,(f1) + 2\,(f2) + 3(f3) \quad (1)$$

where *f1*, *f2* and *f3* are the frequencies (%) of occurrence of $Tabs_{min}$ in each range.

All meteorological data were made compatible with the MODIS images, calculating the means (Rs, T) or totals (r, PET, DEF and FI) for periods of 16 days, grouped by month and season: spring (from September 2nd to December 1st), summer (from December 2nd to March 1st), autumn (from March 2nd to June 1st) and winter (from June 2nd to September 1st). This procedure was performed to allow comparisons among FAR (evaluated every 28 days), MODIS images (obtained every 16 days) and meteorological data (daily data). For the monthly data generation, we considered the mean of the two 16-days composites in the month, with the exception of August, in which only one image was used.

In order to represent the average pattern and the variability of the data series, box plots were prepared for the four seasons, and a Pearson correlation analysis was carried out among variables ($p < 0.05$) for each season separately.

For the analysis of the effects associated with ENSO events on NDVI variability of the Pampa biome grasslands, the hot and cold events of the phenomenon were initially identified. The identification of these events was based on the National Oceanic and Atmospheric Administration (NOAA) classification, which considers the deviation of ± 0.5 °C in the average SST (3-month moving average of anomaly in the Niño 3.4 region, for at least five months) to identify the quarters regarding the seasons (CPC 2016). A case study of the 2009/2010 (El Niño) and of the 2011/2012 (La Niña) ENSO events was carried out, and data on water deficit, NDVI and FAR were graphically represented. The choice criterion was the occurrence of events in very close years and with availability of experimental data. NDVI anomalies were also calculated for each year in relation to the average of the whole period considering the seasons separately. Finally, the years of occurrence of the ENSO phenomenon were identified and NDVI anomaly value was compared to the NDVI standard deviation in the season for testing the significance.

RESULTS AND DISCUSSION

Consistent with the high spatial and temporal variability of the vegetation that composes the Pampa biome natural grasslands (Overbeck et al. 2007), a high temporal variability of NDVI and forage accumulation rate was verified (Figure 2). In this study, these data were used as indicators of the vegetation growth and development.

The differences observed in NDVI among seasons are significant and are associated with the subtropical climate prevailing in the region. As there is no seasonal rainfall in the State (Figure 3e), from the climatic point of view (average condition), the variations in the atmospheric evaporative demand (PET – Figure 3c) throughout the year determine the occurrence of water deficits. Nevertheless, in meteorological terms (condition of a given moment), the high interannual variability of rainfall is an isolated meteorological element most associated with the variability of agricultural production in the RS State (Sentelhas et al. 2015).

The NDVI and the FAR presented lower values during winter, considered the critical season for livestock production in the Pampa biome natural grasslands (Mezzalira et al. 2012). Reduction in NDVI and FAR is mainly determined by the lower availability of energy in the environment, since the hydric issue is not limiting. The lower solar radiation and air temperature (Figure 3a and 3b) lead to a reduction of the biomass available in the fields (Figure 2). In addition, low temperature adverse events (frost index – Figure 3d) may compromise the growth of less tolerant forage species (Huston 2004), contributing to the decrease of NDVI and FAR values in this season.

During spring and summer, the increment in NDVI and FAR values (Figure 2) occurs as a consequence of the higher →

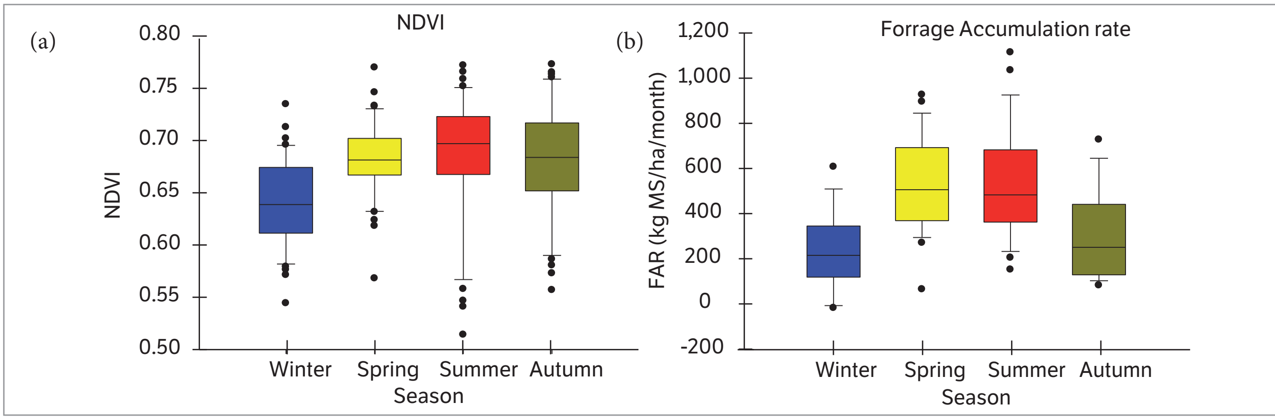

Figure 2. Box plots of the Normalized Difference Vegetation Index (NDVI) and Forage Accumulation Rate (FAR) distribution observed under conditions of moderate forage supply in the four seasons, in Eldorado do Sul, Rio Grande do Sul, Brazil, from 2000 to 2013. The horizontal lines inside the boxes represent the 50th percentile (median); the boxes ends are at the 25th and 75th percentiles; the bars are at the 10th and 90th percentiles; the circles are the extreme values.

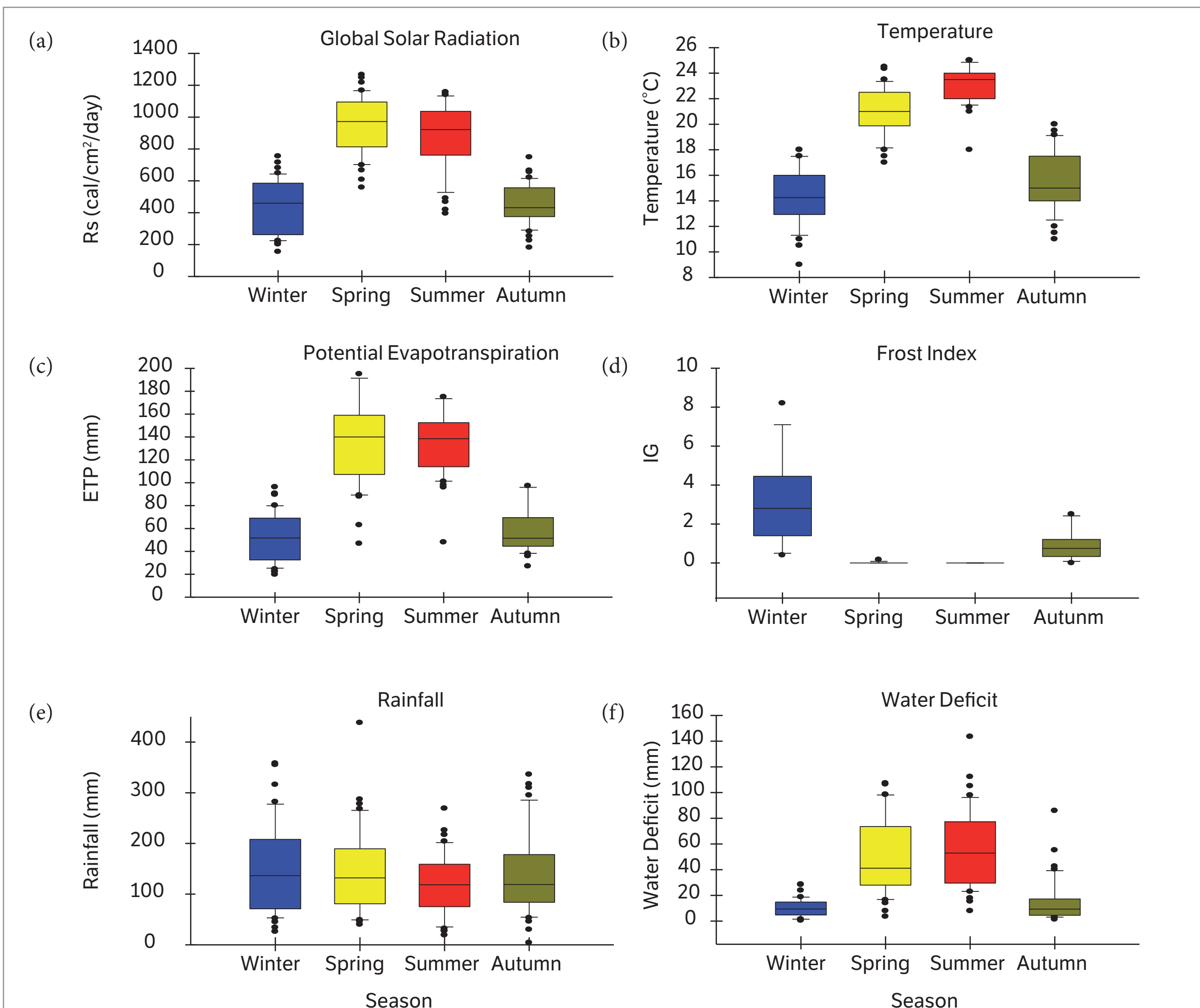

Figure 3. Box plots of the agrometeorological elements distribution in the four seasons, in Eldorado do Sul, Rio Grande do Sul, Brazil, from 2000 to 2013. The horizontal lines inside the boxes represent the 50th percentile (median); the end of the boxes are at the 25th and 75th percentiles; the bars are at the 10th and 90th percentiles; the circles are the extreme values.

energy availability (solar radiation and air temperature), as well as the growth of C4 species in the Pampa biome natural grasslands (Boldrini 1997). However, during summer this increment is often limited, and there were decrease in NDVI and FAR due to the occurrence of water deficits with the more atmospheric evaporative demand (Figure 3f). In these situations, the water limitation in the soil leads to restricted resources for plant growth, which is insufficient (Rueda et al. 2013). The effect of water deficit on the reduction of NDVI values during summer has already been described in similar studies in this region (Wagner et al. 2013; Kuplich et al. 2013), being characterized as the main adverse meteorological event at this season and, therefore, associated with agricultural losses (Berlato and Fontana 2003).

During autumn, the NDVI values were also high and statistically similar to those observed in spring and summer (Figure 2). This result may be associated with the beginning of growth and development of the C3 forage species, with higher concentrations of nitrogen in the leaf mesophyll (Paciullo 2002). In addition, the adverse events, both from thermal (FI) and hydric (DEF) points of view, show a low frequency in this season. Although high levels of NDVI were observed during autumn, a reduction in FAR values in relation to the summer was observed. This response is commonly observed in the Pampa biome natural grasslands due to the low concentration of C3 species in the plant community (Overbeck et al. 2007).

The quantification of the meteorological elements effect on NDVI and FAR throughout the year can be observed through the Pearson correlation analysis (Table 1). It is verified that the highest correlation coefficients were obtained during summer among NDVI and Rs (–0.59), PET (–0.64) and DEF (–0.73), all negatively correlated, indicating, that NDVI is greater in conditions of adequate hydric supply. Also during spring and autumn, the inverse relation between NDVI and DEF was verified. In the other seasons, the correlation coefficients were lower. During autumn, temperature and NDVI showed a positive correlation.

In the analysis by season, the correlation coefficients between meteorological data and FAR were, in general, lower than those observed with NDVI, however, they presented a similar relation pattern. On the other hand, the correlation between NDVI and the FAR was positive and statistically significant in three of the four seasons (summer, autumn and winter). In the annual analysis, the opposite was verified. The correlation coefficients were higher between meteorological data with FAR than with NDVI. Given the similar distribution of rainfall throughout the year, this was the only meteorological element that did not show association with the FAR annual pattern.

These results indicated that the use of spectral indices, associated with agrometeorological elements, similarly to what has been done for annual grain crops (Junges and →

Table 1. Pearson correlation coefficients among forage accumulation rate (FAR, Kg DM/ha/month), NDVI and meteorological variables in Eldorado do Sul, Brazil, presented by seasons. Series from 2000 to 2013.

Parameter	Season				Annual
	Summer	Autumn	Winter	Spring	
NDVI					
Rs	–0.59***	0.01	0.09	–0.20	–0.10
T	–0.15	0.35*	0.24	–0.09	0.10
PET	–0.64***	0.05	0.17	–0.29	–0.13
r	0.29	0.21	0.11	0.04	0.14
DEF	–0.73***	–0.30	0.22	–0.44**	–0.34***
FAR					
Rs	–0.07	0.27	0.16	0.11	0.47***
T	0.04	0.44*	0.19	0.06	0.51***
PET	–0.16	0.25	0.17	0.19	0.45***
r	0.30	–0.04	0.38	–0.05	0.10
DEF	–0.33*	0.10	0.15	0.03	0.24**
NDVI vs FAR	**0.51*** **	**0.44***	**0.51** **	**0.14**	**0.37*** **

Rs: Global solar radiation (cal/cm²/day); T: Air temperature (ºC); PET: Potential evapotranspiration (mm); r: rainfall (mm); DEF: water deficit (mm). * $p < 0.10$; ** $p < 0.05$; *** $p < 0.001$.

Fontana 2011; Mabilana et al. 2012; Klering et al. 2016), is an approach to be tested for the modeling of forage accumulation in natural grasslands. The correlations established in this study indicated which elements should be considered in the natural grasslands growth models adjustment.

With a similar approach, however, using images from the ETM+ sensor aboard the Landsat 7 satellite, Fonseca et al. (2007) proposed a model based on the development of two conceptual models: the submodel of forage production estimation (parameters: photosynthetically active radiation and potential and actual evapotranspiration) and the spectral submodel (parameters: reflectance in the regions of red and near and mid infrared). The parameterized model was sensitive to express the spatial variations in the forage availability and the decrease in production due to the occurrence of water deficit during the period of vegetative growth of the plants in two municipalities of RS State. The contribution of this study is mainly based on the fact that, due to the spatial and temporal resolution of MODIS images, the forage accumulation in the natural grasslands in regional analyzes is evidenced. This scope can contribute to a better understanding of the functioning and, consequently, to actions that seek greater sustainability to the Pampa biome.

Another relevant aspect related to the RS climate is that part of the interannual variability of the meteorological elements is associated to the ENSO phenomenon (Berlato and Fontana 2003), which affects the vegetation growth. In the El Niño event of 2009/2010, the accumulated water deficit during summer was 133 mm, while in the La Niña event that occurred in the following year (2011/2012), the deficit was considerably higher (247 mm). As a consequence of the favorable hydric conditions, the NDVI values were higher during the El Niño event in almost all months of the year (Figure 4). In the case of the La Niña,

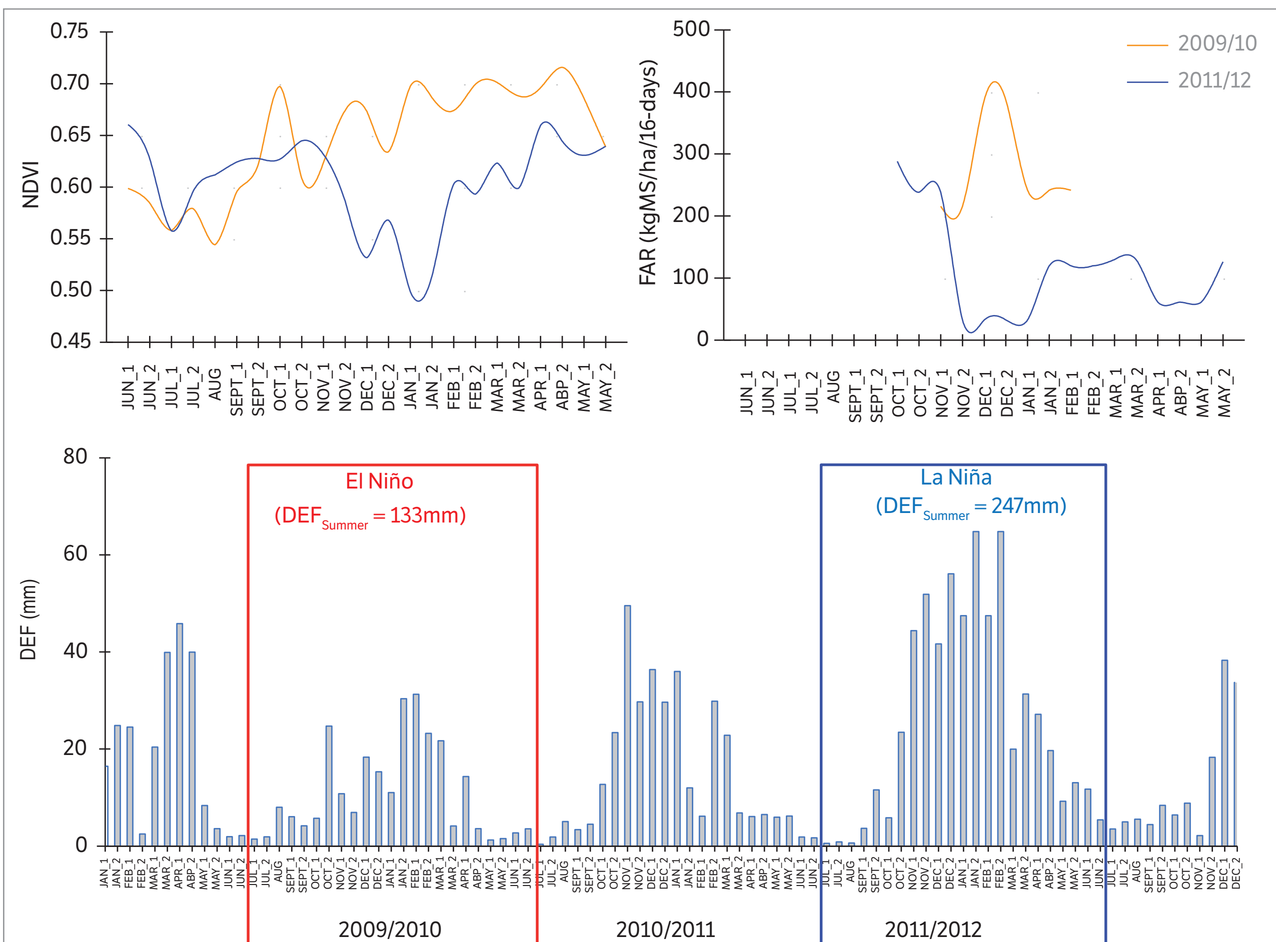

Figure 4. Values of DEF (Water deficit), NDVI (Normalized Difference Vegetation Index) and FAR (Forage Accumulation Rate) observed during the ENSO events of 2009/2010 and 2011/12, in Eldorado do Sul, Rio Grande do Sul, Brazil.

water deficit determined the less availability of forage and, consequently, the lesser NDVI values. On FAR, despite the less data availability when compared to NDVI data in the considered period, the average of the El Niño event (294 kgDM/ha/16 days) was more than double that of the average during the La Niña event (121 kgDM/ha/16 days). The smallest amount of FAR data was due to problems in the collection of experimental data in that year.

The relation between the seasons and ENSO phases (Figure 5) indicated that during autumn, there was higher frequency of NDVI anomalies with higher absolute values, (negatives and positives), generally associated with a neutral condition. This shows that, although there is a high growth variability of natural grasslands, the ENSO phenomenon has little interference even in this season. During summer, a higher frequency of positive anomalies is observed in the evaluated years, however, of low value. The highest negative anomalies in NDVI occurred in this season, one associated with the La Niña in 2012 and another with the El Niño in 2005. In the case of the La Niña, the expected response was observed, with a drought decreasing the growth of the natural grasslands. During the summer of 2005, despite the El Niño classification, a drought was observed in RS State, which explains the low NDVI values. In the studied area, the average rainfall (40 years historical series) is 262 mm in the summer. During the summer of 2004/2005, the rainfall was only 152 mm (58% of the average). A similar result was verified by Kuplich et al. (2013), who observed the lowest values of vegetation index in the years 2004/2005, in relation to the total series analyzed in several regions of natural grasslands in Rio Grande do Sul.

During spring, the anomalies in NDVI and FAR presented a lower magnitude, however, two El Niño events were associated with the positive anomalies, and two La Niña events were associated with a negative anomaly. This is the type of association expected between the ENSO and the vegetation for the southwestern South American conditions (Berlato and Fontana 2003). During winter, both positive and negative anomalies associated with El

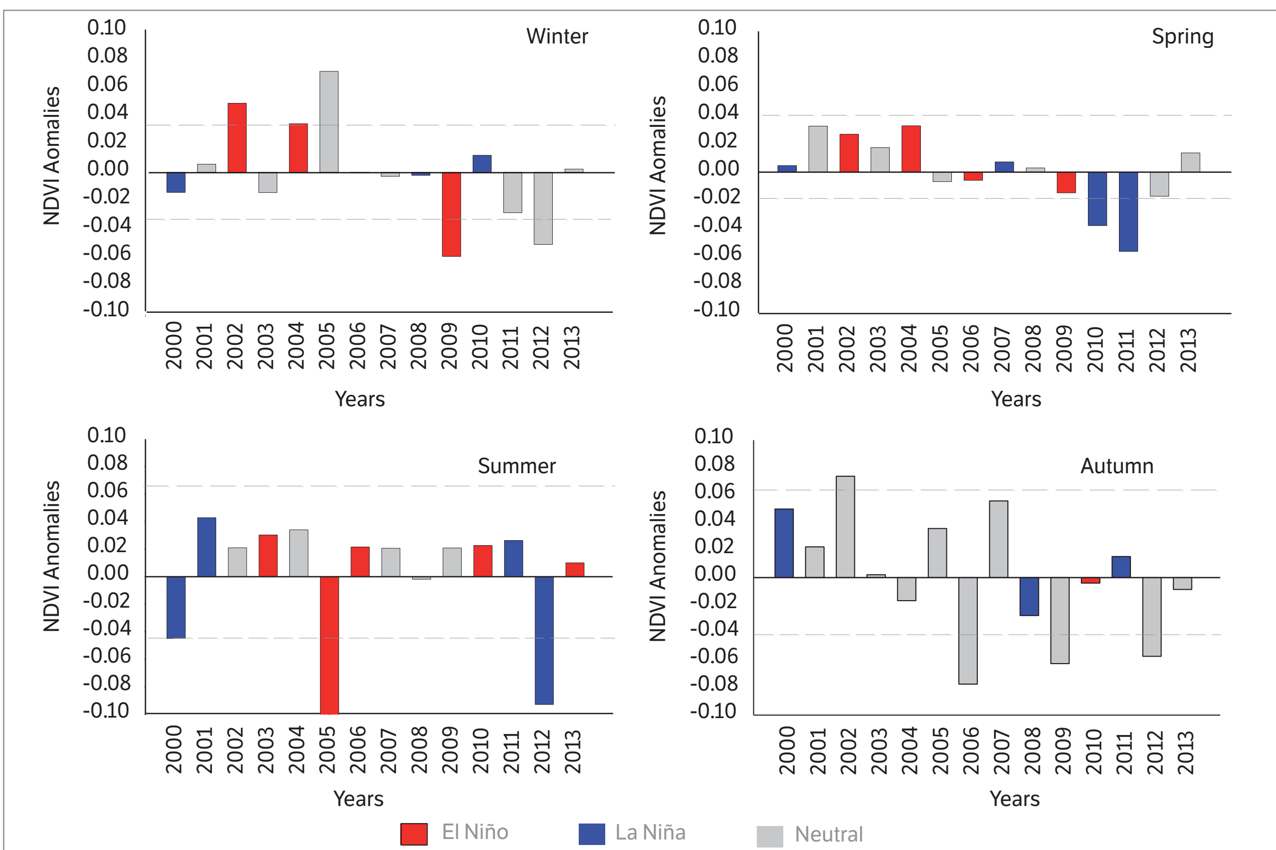

Figure 5. Anomalies of the NDVI average during the period from 2000 to 2013, Eldorado do Sul, Rio Grande do Sul, Brazil. The dashed lines represent the standard deviation for each season.

Niño and Neutral events were observed, and a consistent pattern was not determined.

The results indicate a tendency of negative influence of La Niña events on NDVI values, especially during spring-summer period, due to the occurrence of below-average rainfall. In these years, the occurrence of water deficit may cause less forage accumulation. It is also important to note that, in La Niña years, most of the months present negative air temperature anomalies (up to 1,5 °C), especially in October and November (Berlato and Fontana 2003). The forage species growth during spring may then be impaired by the lower air temperatures in La Niña years, as indicated by the NDVI negative deviations during 2011 spring.

In future works, it is recommended to analyze the effect in the correlations caused by filtering NDVI time series for outliers removal, as well as to introduce the lag between the meteorological variables and the NDVI response.

Considering the possibility of predicting the occurrence of ENSO events with a reasonable level of reliability, we can use the information obtained in this study to support management targets to livestock production in natural grasslands during the prevalence of ENSO event. In RS, the COPAAERGS (Conselho Permanente de Agrometeorologia aplicada do Estado do Rio Grande do Sul) forum brings together technicians at least four times a year to elaborate recommendations on crop, field and orchard management. These recommendations are based on Sazonal Climate Forecast prepared by international institutes, as International Research Institute for Climate and Society. The information provision that serves as a subsidy for the preparation of technical recommendations may contribute to the conservation and sustainability of the Pampa biome.

The results presented confirmed the expected trends in terms of natural grasslands responses to weather and climate conditions. The main contribution of this study is to confirm the viability of the use of free and available in near real time orbital images to infer about the natural grasslands condition in the south of Brazil. Such information can be used by farmers to align management practices, or by decision makers in the sector.

CONCLUSION

The agrometeorological element associated to forage accumulation in the Pampa biome natural grasslands is different according to the season, which is typical of the predominant subtropical climate in the region.

Winter is the critical season for livestock production due to lower forage accumulation rate and lower NDVI values, conditioned by solar radiation and air temperature decrease. During summer, the limiting factor for natural grasslands growth is the hydric condition.

There is variability in the meteorological conditions associated with the ENSO phenomenon. The El Niño is favorable and the La Niña is unfavorable for growth of natural grasslands, especially during spring-summer period.

The combined use of spectral indices with agrometeorological elements is recommended for fitting forage accumulation models in the Pampa biome natural grasslands.

ACKNOWLEDGEMENTS

To CNPq and FAPERGS, for granting financial resources and scholarships.

ORCID IDs

D. C. Fontana
https://orcid.org/0000-0002-2635-6086
A. H. Junges
https://orcid.org/0000-0001-6982-7880
C. Bremm
https://orcid.org/0000-0002-7612-2771
L. P. Schaparini
https://orcid.org/0000-0003-4799-7496
V. P. Mengue
https://orcid.org/0000-0002-2955-1039
A. P. L. Wagner
https://orcid.org/0000-0002-6804-4830
P. Carvalho
http://orcid.org/0000-0002-7020-3001

REFERENCES

Berlato, M. A. and Fontana, D. C. (2003). El Niño e La Nina: impactos no clima, na vegetação e na agricultura do Rio Grande do Sul; aplicações de previsões climáticas na agricultura. Porto Alegre: Editora da UFRGS.

Berra, E. F., Fontana, D. C. and Pereira, R. S. (2014). Accuracy of forest stem volume estimation by TM/Landsat imagery with different geometric and atmospheric correction methods. Journal of applied science and technology, 4, 108-116.

Boldrini, I. I. (1997). Campos do Rio Grande do Sul: caracterização fisionômica e problemática ocupacional. Boletim do Instituto de Biociências, 56, 1-39.

Carvalho, P. C. F. (2013). Harry Stobbs Memorial Lecture: can grazing behavior support innovations in grassland management? Tropical Grasslands, 1, 137-155. https://doi.org/10.17138/tgft(1)137-155.

Climate Prediction Center NOAA. (2016) Cold and Warm episodes by season. Available at: http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php. Accessed on Mar. 15, 2016.

Cunha, G. R., Pires, J. L. F, Pasinato, A. and Dalmago, G. A. (2005). Variabilidade temporal e espacial do quociente fototermal no Rio Grande do Sul e suas implicações para a expressão do potencial de rendimento de grãos de trigo. Revista Brasileira de Agrometeorologia. 13, 91-101.

Fonseca, E. L., Ponzoni, F. J. and Formaggio, A. R. (2007). Modelo agrometeorológico-espectral para estimativa da disponibilidade de forragem no bioma “Campos Sulinos”. Revista Brasileira de Agrometeorologia, 15, 241-249.

Huston, M. A. (2004). Management strategies for plant invasions: manipulating productivity, disturbance, and competition. Divers and Distributions, 10, 167-178. https://doi.org/10.1111/j.1366-9516.2004.00083.x.

Instituto Brasileiro de Geografia e Estatística (2017). Produção da Pecuária Municipal. Available at: http://www.sidra.ibge.gov.br. Accessed on May 10, 2017.

Junges, A. H., Bremm, C., Fontana, D. C., Schaparini, L. P. and Carvalho, P. C. F. (2016). Temporal profiles of vegetation indices for characterizing grazing intensity on natural grasslands in Pampa biome. Scientia Agricola, 73, 332-337. http://dx.doi.org/10.1590/0103-9016-2015-0213.

Junges, A. H. and Fontana, D. C. (2011). Modelo agrometeorologico-espectral de estimativa de rendimento de grãos de trigo no Rio Grande do Sul. Revista Ceres, 58, 9-16. http://dx.doi.org/10.1590/S0034-737X2011000100002.

Junges, A. H., Fontana, D. C. and Pinto, D. G. (2013). Identification of croplands of winter cereals in Rio Grande do Sul state, Brazil, through unsupervised classification of normalized difference vegetation index images. Engenharia Agrícola, 33, 883-895. http://dx.doi.org/10.1590/S0100-69162013000400027.

Klering, E. V., Fontana, D. C., Roglio, V. S., Alves, R. C. M. and Berlato, M. A. (2016). Agrometeorological-spectral model to estimate irrigate grain yield in the State of Rio Grande do Sul, Brazil. Bragantia, 76, 247-256. http://dx.doi.org/10.1590/1678-4499.287.

Klingman, D. L., Miles, S. R. and Mott, G. O. (1943). The cage method for determining consumption and yield of pasture herbage. Journal of American Society of Agronomy, 35, 739-746.

Kuplich, T. M., Moreira, A. and Fontana, D. C. (2013). Série temporal de índice de vegetação sobre diferentes tipologias vegetais no Rio Grande do Sul. Revista Brasileira de Engenharia Agrícola e Ambiental, 17, 1116-1123. http://dx.doi.org/10.1590/S1415-43662013001000014.

Mabilana, H. A., Fontana, D. C. and Fonseca, E. L. (2012). Desenvolvimento de modelo agrometeorológico espectral para estimativa de rendimento do milho na Província de Manica-Moçambique. Revista Ceres, 59, 337-349. http://dx.doi.org/10.1590/S0034-737X2012000300007.

Mengue, V. P. and Fontana, D. C. (2015). Avaliação da dinâmica espectro-temporal visando o mapeamento dos principais cultivos de verão no Rio Grande do Sul. Bragantia, 74, 331-340. http://dx.doi.org/10.1590/1678-4499.0452.

Mezzalira, J. C., Carvalho, P. C. F., Trindade, J. K., Bremm, C., Fonseca, L., Amaral, M. F. and Reffatti, M. V. (2012). Produção animal e vegetal em pastagem nativa manejada sob diferentes ofertas de forragem por bovinos. Ciência Rural, 42, 1264-1270. http://dx.doi.org/10.1590/S0103-84782012005000039.

National Aeronautics and Space Administration (2016). Earthdata Search. Available at: http://reverb.echo.nasa.gov/reverb/redirect/wist. Accessed on Mar. 14, 2016.

Overbeck, G. E., Müller, S. C., Fidelis, A., Pfadenhauer, J., Pillar, V. D., Blanco, C. C., Boldrini, I. I., Both, R. and Forneck, E. D.

(2007). Brazil's neglected biome: the South Brazilian Campos. Perspective in plant ecology evolution systematics, 9, 101-116. https://doi.org/10.1016/j.ppees.2007.07.005.

Penman, H. L. (1956). Evaporation: an introductory survey. Netherland Journal of Agricultural Science, 4, 9-29.

Paciullo, D. S. C. (2002). Características anatômicas relacionadas ao valor nutritivo de gramíneas forrageiras. Ciência Rural, 32, 357-364. http://dx.doi.org/10.1590/S0103-84782002000200029.

Pilar, V. P. and Vélez, E. (2010). Extinção dos Campos Sulinos em unidades de conservação: um fenômeno natural ou um problema ético? Brazilian journal of nature conservation, 8, 84-86. http://doi.ogr/10.4322/natcon.00801014.

Rueda, M., Rebollo, S. and García-Salgado, G. (2013). Contrasting impacts of different-sized herbivores on species richness of Mediterranean annual pastures differing in primary productivity. Oecologia, 172, 449-459. http://doi.org/10.1007/s00442-012-2501-y.

Santos, J. S., Fontana, D. C., Silva, T. S. F. and Rudorff, B. F. T. (2014). Identificação da dinâmica espaço-temporal para estimar área cultivada de soja a partir de imagens MODIS no Rio Grande do Sul. Revista Brasileira de Engenharia Agrícola e Ambiental, 18, 54-63. http://dx.doi.org/10.1590/S1415-43662014000100008.

Scottá, F. C. and Fonseca, E. L. (2015). Multiscale trend analysis for Pampa grasslands using ground data and vegetation sensor imagery. Sensors, 15, 17666-17692. http://doi.org/10.3390/s150717666.

Sentelhas, P. C., Battisti, R., Câmara, G. M. S., Farias, J. R. B., Hampf, A. C. and Nendel, C. (2015). The soybean yield gap in Brazil – magnitude, causes and possible solutions for sustainable production. The journal of agricultural science, 153, 1394-1411. https://doi.org/10.1017/S0021859615000313.

Soudani, K., Hmimina, G., Delpierre, N., Pontailler, J. Y., Aubinet, M., Bonal, D., Caquet, B., Grandcourt, A., Burban, B., Flechard, C., Guyon, D., Granier, A., Gross, P., Heinesh, B., Longdoz, B., Loustau, D., Moureaux, C., Ourcival, J. M., Rambal, S., Saint André, L. and Dufrêne, E. (2012). Ground-based Network of NDVI measurements for tracking temporal dynamics of canopy structure and vegetation phenology in different biomes. Remote sensing of environment, 123, 234-245. https://doi.org/10.1016/j.rse.2012.03.012.

Thornthwaite, C. W. and Mather, J. R. (1955). The water budget and its use in irrigation. In Stefferud, A. (Ed.), The Yearbook of Agriculture (p.346-358). Washington: The United States Department of Agriculture.

Universidade Federal do Rio Grande do Sul (2016). Dados Meteorológicos da Estação Experimental Agronômica. Available at: http://www.ufrgs.br/agronomia/joomla/index.php/eea-pesquisa. Accessed on Mar. 14, 2016.

Wagner, A. P. L., Fontana, D. C., Fraisse, C.; Weber, E. J. and Hasenack, H. (2013). Tendências temporais de índices de vegetação nos campos do Pampa do Brasil e do Uruguai. Pesquisa Agropecuária Brasileira, 48, 1192-1200. http://dx.doi.org/10.1590/S0100-204X2013000900002.