



# Implications of landscape configuration on understory forage productivity: a remote sensing assessment of native forests openings

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**Abstract** Sound management of native forests used for cattle grazing requires understanding the dynamics of forage productivity in the openings. Despite their importance, forage productivity drivers in highly heterogeneous forested landscapes, or their variability over the year, are still unclear. The aim of this work is to find predictors of Normalized Difference Vegetation Index (NDVI) variation in the openings of native temperate forests and to evaluate how these predictors change within the growing season. We used high

spatial resolution remote sensing imagery from NW Patagonia to separate forest openings from tree dense canopy. We obtained data of each opening related with herbaceous and shrub forage productivity and calculated landscape metrics. We estimated a multiple linear regression model for predicting NDVI in each season. Beyond known variables related with forage productivity (altitude, precipitation, etc.), the shape of forest' openings appeared as relevant in predicting NDVI. Higher values of forest opening perimeters were related with a decrease in NDVI in spring when soil water content is not limiting and conversely with an increase in NDVI in summer when water is limiting

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growth. These results suggest that environmental drivers such as temperature and soil moisture inside the opening, and competition or facilitation process between trees and grasses are mediated by the shape of the opening. Management of heterogeneous native forests for cattle raising requires considering the shape of the openings to maximize forage productivity.

**Keywords** Cattle · Grazing · NDVI · Heterogeneity · Seasonality · Temperate forests

## Introduction

Estimating appropriate carrying capacities in heterogeneous native forests is key to designing sound management schemes. Native forests worldwide are widely used for livestock grazing as they offer different sources of forage (Murgueitio 2005; Araújo et al. 2016; Cameron 2016; Peri et al. 2016a; Bussoni et al. 2019; Iglay et al. 2019). Assessing overall forage productivity in forest ecosystems is key to estimate sound stocking rates, including management planning and decisions on resting periods or exclosures, necessary to achieve a higher overall forage productivity and to avoid forest degradation (La Manna et al. 2008; Peringer et al. 2016). In temperate forests, such as NW Patagonia forests, less dense canopy areas or purposive forest clearings favor herbage and shrub productivity, where most of the grazing concentrates, including shrub browsing which is particularly important in winter when snow covers the herbaceous vegetation. These sites are the object of our study and henceforth referred to as ‘forest openings’. Estimating herbaceous and shrub forage biomass productivity in these openings at regional and field scale presents methodological challenges, especially in mountainous landscapes subject to high spatio-temporal climatic variability.

Forage availability throughout the year is often estimated through mathematical equations that consider the regional variation in environmental drivers such as precipitations, temperature or soil quality (Golluscio 2009). However, in high heterogeneous forested landscapes there may be other ‘local’ drivers that simultaneously affect plant biomass productivity, such as microclimate within forest openings varying in size, shape, hillside exposition, slope and altitude.

Most studies relate regional variation in rainfall or altitude with overall forage productivity, in order to estimate carrying capacity in forest openings (e.g., Thompson et al. 1991; Masters et al. 1999; Greenberg et al. 2011; Wangchuk et al. 2015). Less frequent are the studies that relate landscape variables with vegetation attributes as affected also by the traits of the openings (Özcan y Gökbülak 2017), such as their species composition or the specific features of the forest–grassland interface (heterogeneity, tree density, etc.).

The existence of such open areas surrounded by tree dense canopy means that biophysical drivers can operate at different scales. While regional variation in precipitation or altitude can affect forage productivity potential at a given opening, its actual productivity may be also affected by drivers that operate at a finer scale, such as air temperature, humidity and wind speed inside the opening, determining the ‘opening microclimate’ (Geiger et al. 2009). These drivers are mainly determined by landscape metrics such as area, perimeter and convexity of the opening (Perry 1994; Chen et al. 1999). In addition, competition or facilitation process might occur between trees belonging to the opening’s border and herbaceous and shrubby vegetation growing inside the opening, reducing or increasing opening’s vegetation productivity, respectively. For example, Özcan and Gökbülak (2017) found that vegetation characteristics growing inside the opening depended on forest opening size. Therefore, we hypothesize that forage productivity inside the opening is affected by landscape variables such as opening’ size and shape, and the amount of tree border of the opening.

Additionally, changes in the effects of drivers on forage productivity may differ among seasons. For example, a reduction in rainfall may not affect biomass productivity at the beginning of the growing season, but can decrease it toward the end of the growing season (Ludewig et al. 2015), whereas temperature can affect biomass growth through seasonal stresses in extreme cold or hot periods (Ergon et al. 2018). Local landscape variables, such as the shape and size of the opening, may moderate water and temperature regimes within the openings, through, e.g., shading in summer or reducing wind speed in winter. Hence, the interplay between regional and landscape drivers and their effect over forage

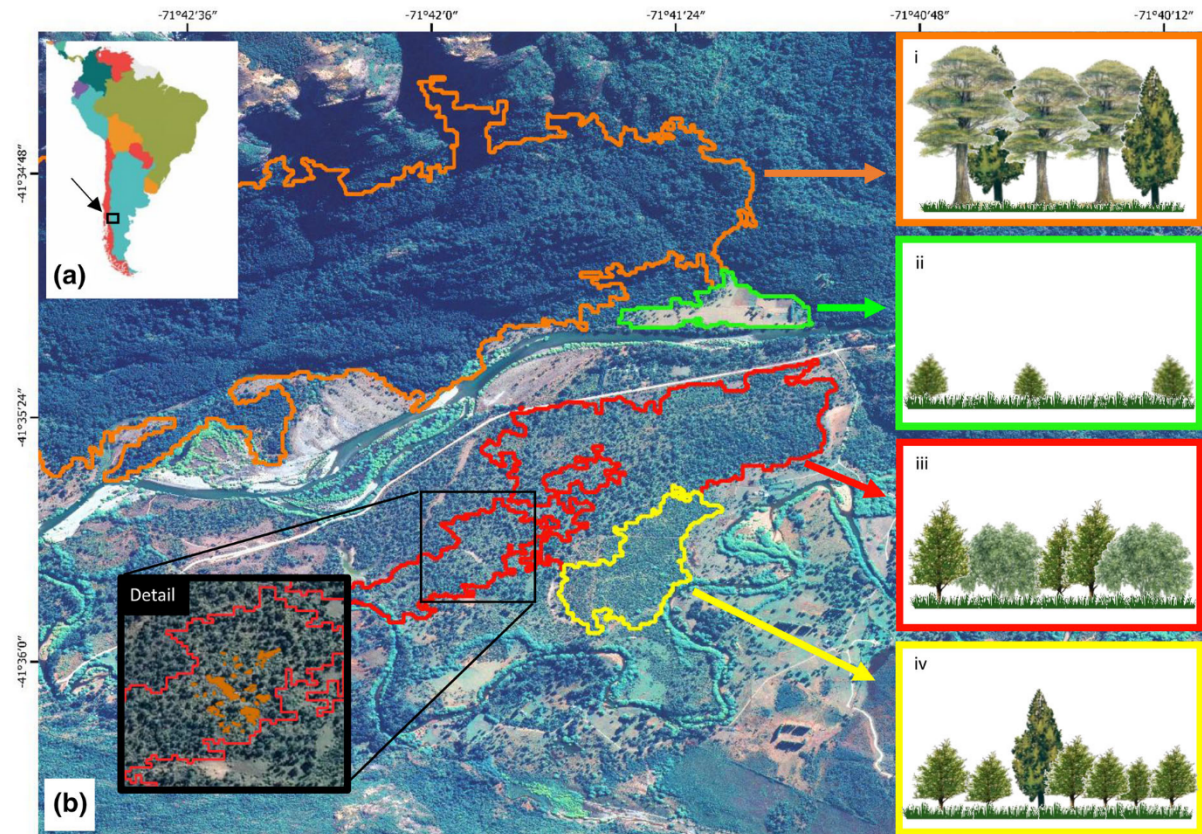
productivity may vary depending on the period analyzed, and this variation is still unexplored.

With the aim of being able to inform sound livestock management in heterogeneous native forests, our objective is to assess the variability of herbaceous and shrub biomass produced in forest openings as affected by both regional and local variables, their interplay, their relative importance and whether the effects of these predictors change along the growing period, in two case study valleys within North Patagonia native temperate forests.

**Materials and methods**

The study area covers temperate native forests of NW Patagonia, Argentina, and comprises the El Manso and Foyel valleys (NW vertex: S41°30', W71°45'; SE

vertex S41°51', W71°20', Fig. 1a). This area has many native forest types, already classified by the species composition (SAyDS & CIEFAP 2016, Fig. 1b), and is largely used for cattle grazing. Further, grazing patterns found within the study area are heterogeneous and can modify vegetation species composition (Bestelmeyer et al. 2003; Piazza et al. 2016; Rusch et al. 2016). Study area has a wide variation in regional variables, such as soil types, altitudes, annual mean temperatures and precipitations (Godagnone and Bran, 2009). Precipitation fall mainly in winter (494 mm), and summer is usually dryer (144 mm). Mean temperature ranges from 3.8 in winter to 15.2 °C in summer (Bianchi et al. 2016). This climate makes spring the period of maximum vegetation growth because water availability is not limiting, and the temperature is high enough. Nevertheless, soil water deficiencies in late summer might limit strongly



**Fig. 1** a Study area location. b Example of different vegetation types appearing in a subset of the study area. Background map: satellite image. Border colored polygons: 4 different vegetation types. Only 4 of total 16 vegetation types analyzed are shown in

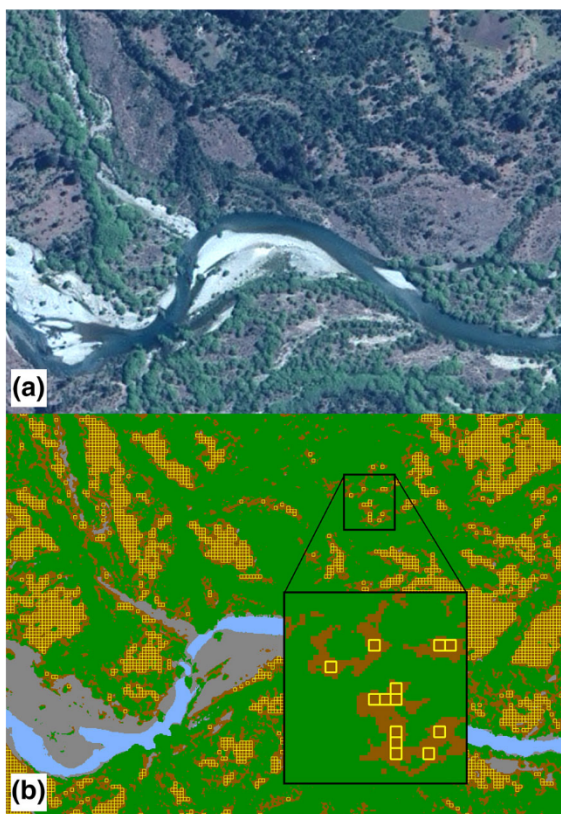
this figure as an example: (i) High mixed forest, (ii) Grassland, (iii) Mixed medium forest, (iv) Scrub with some trees of medium height. Detail: some forest openings are orange filled as an example, they are the object of our study

vegetation growth in some areas (Licata et al. 2008; Martinez-Meier et al. 2015). Thus, the growing season of our study area starts in spring and ends in late summer.

For separating openings from tree dense canopy, we made a supervised classification. To visualize and separate dense tree canopy from openings with high accuracy, we used SPOT7 imagery, because it has a high spatial resolution compared with other sensors: 1.5 and 6 m for panchromatic and multispectral bands, respectively. To maximize class separation capacity, we employed a pan sharpening Gram Smith method with both panchromatic and multispectral images with ENVI 5.3© (Maurer 2013, Fig. 2a). To make an optimal classification, we used a free cloud image dated February 10, 2017. We used the new pan-




sharpened image to make a neural-net supervised classification. This type of classification achieves an accurate class separation capacity if made with high spatial resolution imagery (Postadjian et al. 2017). With training data of openings, canopy, water and rock, we created a four-class neural-net supervised classified image with ENVI 5.3© (Fig. 2b). In order to obtain openings shape indexes, we used the feature extraction module from ENVI 5.3© to get the vectors of the openings classified and their shapes attributes (Tables 1 and 2, see Online Resource 1). In order to find those variables with more explanatory power, we kept all landscape metrics of each opening.

We estimated vegetation biomass productivity in forest openings through the Normalized Difference Vegetation Index (NDVI). ‘Productivity’ is defined as the instant vegetation biomass production, directly related with NDVI, while ‘overall biomass productivity’ is defined as the production of vegetation in a more extent time lapse, for example, one year, per unit area (Pettorelli et al. 2005). In forest openings, the correlation between NDVI and ground biomass productivity is positive because most of the photosynthetic activity comes from grasses and shrubs and is captured by the sensors, conversely to dense forested canopy areas (Borowik et al. 2013). Despite NDVI saturates at high-density pasture levels, it can be used as a predictor of forage productivity in forest openings whenever it is obtained avoiding the capture of information of dense tree canopy areas (Hanna et al. 1999, Easdale y Aguiar 2012; Garrouette et al. 2016, Robinson et al. 2019).



**Fig. 2** **a** Detail of the pan-sharpened image obtained from SPOT7. © imagery. Green areas represent dense tree coverage and brown areas represent forest openings. **b** The same zone as “a” after classification. green = dense canopy, brown = opening, light blue = water, gray = rock. Small yellow squares: SPOT7 pixels selection inside the openings, used to calculate NDVI. ©CNES 2016 & 2017, reproduced by CONAE under Spot Image/AIRBUS license

**Table 1** Examples of variation in shape’s indexes among different forms

Opening shape			
Area (m <sup>2</sup> )	1000	1000	1000
Elongation	Low	High	Medium
Perimeter/area	Low	Medium	High
Form factor	High	Medium	Low
Solidity	High	Medium	Low
Convexity	High	Medium	Low
Compact	High	Medium	Low

**Table 2** Variables names, types and ranges for the 5966 forest openings analyzed

Variable name	Minimum	Mean	Maximum
Regional variables			
Vegetation type	–	–	–
Altitude (m)	408.3	862.1	1400.0
Mean annual precipitation (mm)	1025.6	1380.2	2029.4
Mean annual potential evapotranspiration (mm)	396.0	550.0	630.0
Slope (°)	0.0	17.2	66.8
Aspect (°)	– 1.0	0.1	1.0
Mean annual temperature (°C)	1.7	6.9	9.4
Landscape variables			
Perimeter (m)	36	213	25,920
Area (m <sup>2</sup> )	65.2	1055.6	352,269.0
Perimeter/area	0.061	0.320	0.622
Form factor	0.005	0.320	0.698
Compact	0.042	0.179	0.266
Convexity	1072	1482	8726
Solidity	0.192	0.759	0.961
Elongation	1000	1691	14,786
Major axis length (m)	10.1	46.7	1341.4
Minor axis length (m)	7.5	27.3	559.9
Main direction (°)	0.0	87.1	180.0
Number of holes	0.0	0.8	344.0
Hole solidity	0.669	0.996	1.000
Rectangular fit	0.136	0.551	0.863
Response variables			
NDVI spring	0.000	0.266	0.650
NDVI summer	0.098	0.386	0.675
NDVI late summer	0.000	0.393	0.757

For variables definitions and data acquisition methodology, see Online Resource 1 and 2, respectively

In order to study contrasting situations within the growing season because of different temperatures and soil moistures (Martinez-Meier et al. 2015), we calculated NDVI of the openings in three different seasons: i) Spring (12 October 2017), high soil moisture: 79,6 mm recorded within the last 30 days and low evapotranspiration; ii) Summer (10 February 2016), medium soil moisture: 17,8 mm precipitations recorded within the last 30 days and high evapotranspiration; iii) Late summer (20 March 2016), low soil moisture: no precipitation events were recorded in a 30 day window. Precipitation events detailed before were obtained from two local stations from El Manso valley (SIPHN 2019). We used high spatial resolution SPOT7 images, selecting those with no clouds in the entire study area, so the NDVI calculations were reliable to predict photosynthetic activity (Pettorelli

et al. 2005). The NDVI of each opening for each date was calculated as the mean of all the pixels inside the opening with QGIS3.8© (Fig. 2b). In order to avoid mixed pixels (mixed = herbs/shrubs + trees), only those pixels contained completely inside the openings (only herbs/shrubs) were used to calculate the NDVI mean of the opening; this operation was made with QGIS3.8© (Fig. 2b).

Additionally, we collected and calculated environmental attributes of all the polygons classified as forest openings from different sources toward relating it with vegetation productivity (Table 2, see Online Resource 2). To classify each opening by its vegetation type, we used the classification done by SAyDS & CIEFAP (2016) which was made with information of the species composition. We analyzed a dataset of forest openings located in 16 different vegetation classes

below 1400 m.a.s.l. most used for cattle grazing (see Fig. 1 and Online Resource 3, SAyDS & CIEFAP 2016). Because the number of openings to analyze was high ( $n = 26,228$ ), we omitted those with incomplete data, and then, we made a random sample within the complete study area selecting a maximum of 375 openings of each vegetation type. Final number of forest openings analyzed was 5966. Variables ranges obtained and calculated for these openings are found in Table 2.

In order to explore the data and the correlation between variables as there might be nonlinear relationships, we used Non-metric Multi-Dimensional Scaling (NMDS) through the “Bray” method to calculate a dissimilarity matrix (Oksanen 2015). As a first step, we made an ordination of all the openings selected for analysis including all regional and landscape predicting variables over three axes; this step is comparable with a Principal Component Analysis; the advantage of NMDS is that it works adequately with nonlinear relationships between variables. As a second step, we fitted the NDVI values and different vegetation types over the first ordination. To get a better correspondence between variables and NMDS axes, we made a rotation of NMDS results. We calculated the correlation between variables and confidence ellipses with a confidence level of 0.95 for each vegetation type after their ordination over NMDS axis. We used the ‘vegan’ package (version 2.5-5) in R3.5.2© (Oksanen 2015).

For selecting the most important variables that explain NDVI, we used a multiple linear regression model for each season (Anderson et al. 2012). In order to avoid multi-collinearity, for all models we selected a subset of variables so they had a variance inflation factor lower than 3 (Garibaldi et al. 2019). Raw environmental measures were used in this analysis (e.g., mean annual temperature); derived measures were not included due to high collinearity with the raw measures (e.g., mean annual potential evapotranspiration). We made a multimodel inference (Garibaldi et al. 2017) and then calculated the importance of each variable for each season. We defined seven variables to predict NDVI over all seasons by selecting those that summed the highest importance along all seasons. In all cases, we tested models’ assumptions: normality by Kolmogorov’s Distribution test (Marsaglia et al. 2003); independence, variance homogeneity and linearity by plotting residuals vs. predicted (Garibaldi

et al. 2019). We used ‘MuMIn’ package (version 1.43.6) in R3.5.2©.

## Results

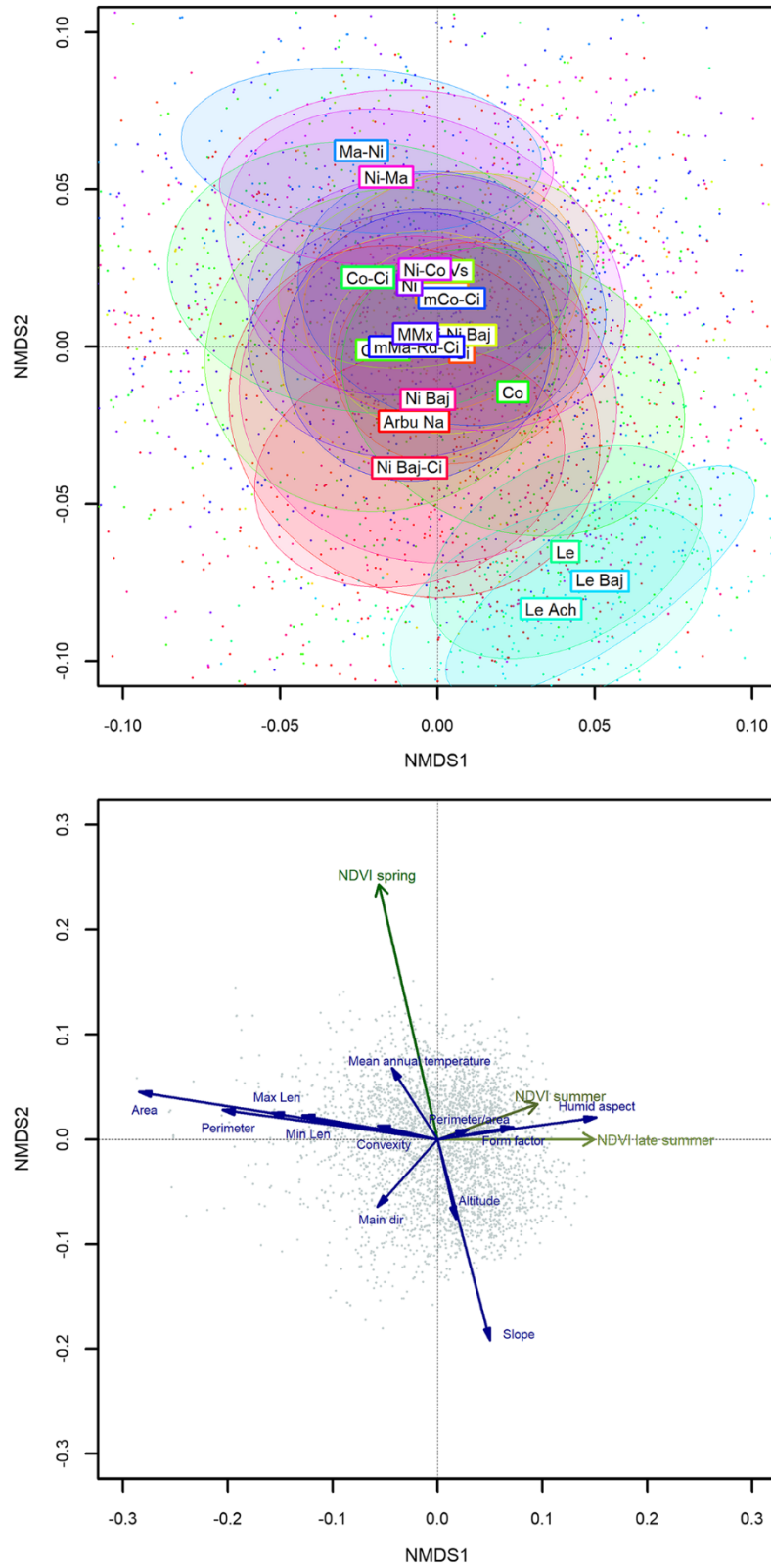
Data exploration with non-metric multi-dimensional scaling: correlation between predictors and NDVI

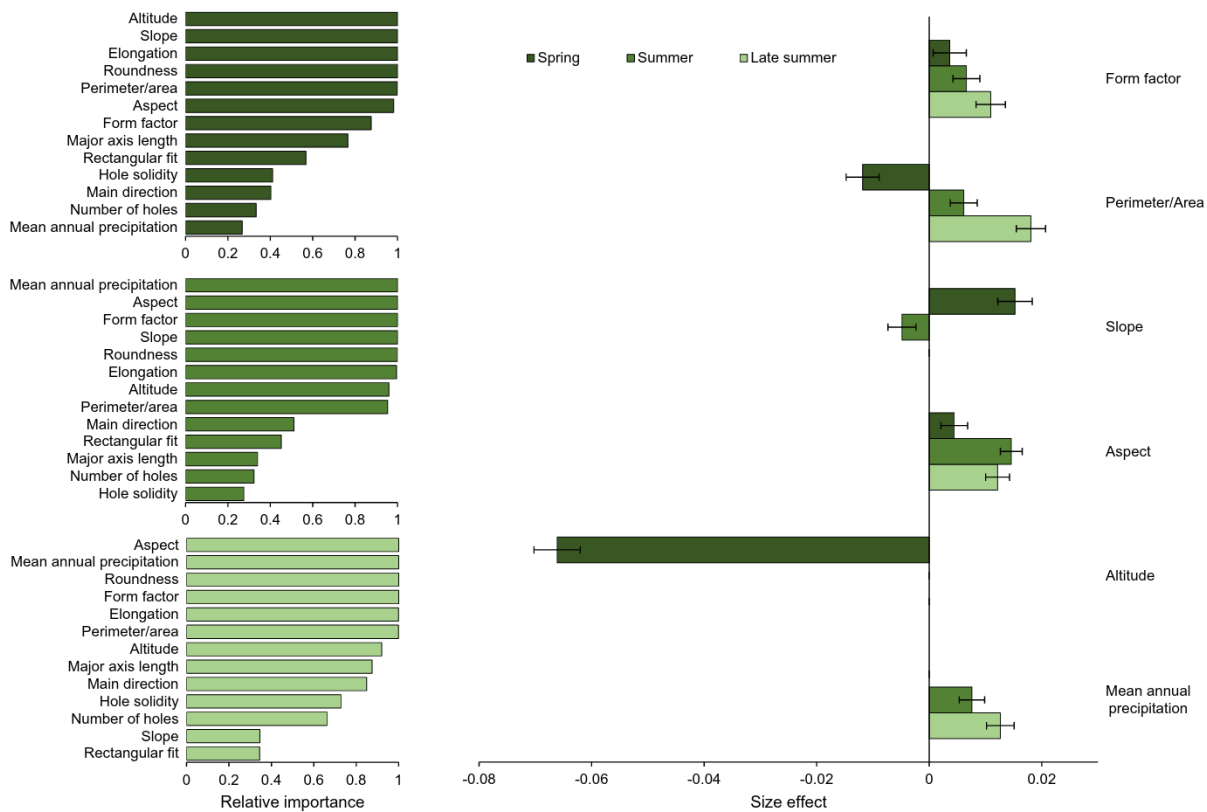
Regional and landscape variables (Table 2) were related with NDVI, and the correlation of each variable with NDVI depended on the season (Fig. 3). NDVI goodness of fit ( $R^2$ ) over NMDS 3-axis ordination indicates how much the NDVI values fit the first ordination; their values corresponded to 0.27, 0.06 and 0.10 for spring, summer and late summer, respectively. Spring NDVI correlated positively with temperature (corr = 1.00,  $p$  value < 0.04), but negatively with altitude (corr = 1.00,  $p$  value < 0.06) and slope. Summer and late summer NDVI were negatively correlated with area (corr < - 0.86,  $p$  value < 0.34) and perimeter (corr < - 0.86,  $p$  value < 0.34). Complete NMDS results are shown in the Online Resource 4.

NDVI prediction with multiple linear regression models

Multiple linear regression of NDVI against explanatory variables had  $R^2$  adj. values of 0.54, 0.31 and 0.26 for spring, summer and late summer, respectively. Vegetation type was the most important variable explaining NDVI in forest openings. This single variable accounted for 45%, 26% and 16% of the NDVI variance in spring, summer and late summer, respectively. The seven predicting variables that summed the highest importance across all seasons explaining NDVI ordered by decreasing importance were: vegetation type, aspect, altitude, form factor, perimeter/area ratio, elongation and mean annual precipitation. After vegetation type, openings’ altitude, slope and three landscape variables (elongation, roundness and perimeter/area) had the highest relative importances in the model of spring, while mean annual precipitation, aspect and four landscape variables (roundness, form factor, elongation and perimeter/area) had the highest relative importances in the model of late summer (Fig. 4, left).

**Fig. 3** First plane of the Non-metric Multi-Dimensional Scaling (NMDS) ordination of forest openings characterized by regional and landscape variables. Each dot represents a forest opening. Upper panel: confidence ellipses (confidence level = 0.95) for each vegetation type analyzed. Each vegetation type has a defined color. Bottom panel: Predicting variables plotted with blue filled arrows and NDVI adjustments plotted with green simple arrows. Arrow coordinates indicates correlation with NMDS axis. Definition of variables and vegetation types can be found in Online Resources 1 and 3, respectively





**Fig. 4** Results of multiple linear regression models for estimating NDVI in forest openings in three different dates. Relative importances of predicting variables of NDVI (left) and size effects of the set of quantitative variables that summed the

highest importances along all seasons (right). Bars indicate 95% confidence intervals. Size effects containing zero in their 95% confidence intervals are shown as null effects.

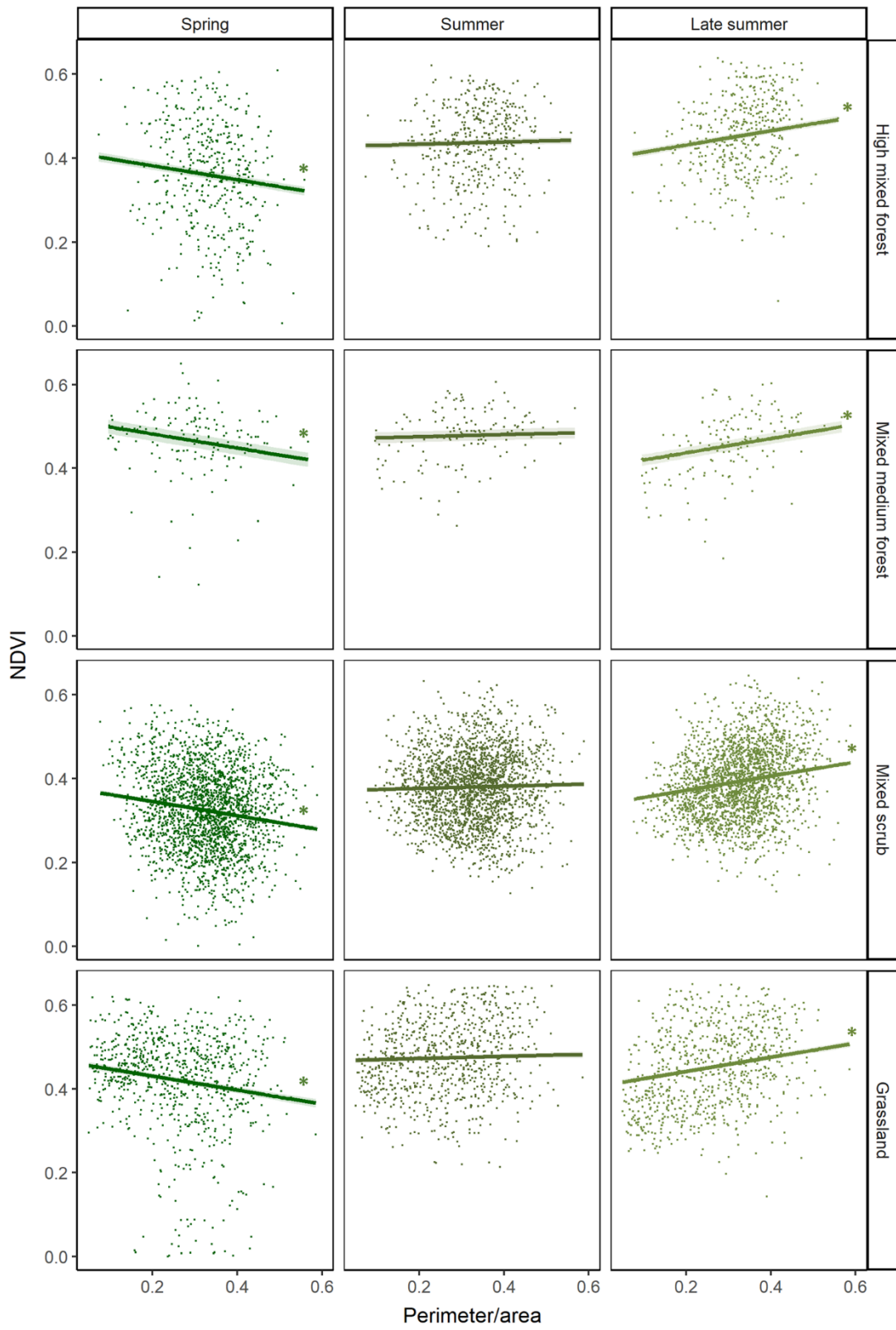
Models showed differences in size effects of the predicting variables over the seasons. In spring, the higher size effect was for a negative effect of altitude over NDVI, followed by the negative effect of the perimeter/area ratio (Fig. 4, right). Mean annual precipitation, aspect, form factor and perimeter/area ratio showed the highest positive size effects on NDVI in summer and late summer (Fig. 4, right). Perimeter/area ratio varied its sign and size effect depending on the season. It showed a negative effect over NDVI in spring ( $p < 0.001$ ) which turned into positive in late summer ( $p < 0.001$ ). Relationships between perimeter/area ratio and NDVI of forest openings are shown with an example in Fig. 5 for only 4 of 16 total vegetation types analyzed. For complete models' outputs, see Online Resource 4.

**Fig. 5** Forest openings NDVI predictions in different seasons, varying perimeter/area ratio and keeping the rest of the predicting variables in their mean values. Figure only shows 4 of total 16 vegetation types analyzed, the same as Fig. 1. Lines and shadows indicate linear model predictions and confidence intervals (95%), respectively. (\*) Indicates significant effect ( $p < 0.001$ )

**Discussion**

Our results confirm the hypothesis that herbaceous and shrub biomass productivity in forest openings, estimated through NDVI, is not only explained by regional variables such as vegetation type, altitude or precipitation but also by landscape metrics that reflect the shape, size and configuration of the openings. Moreover, our results show that the best set of variables to predict NDVI vary over different seasons, as do their relative effect on NDVI.





Vegetation type appeared as the most important variable determining NDVI in forest openings. This variable is associated with forage productivity drivers such as different soil types, species composition and grazing patterns found within the study area (Bestelmeyer et al. 2003; Briske et al. 2005; Fong-Long y Chang-Ching 2018; Yu et al., 2020). On the one hand, in both NMDS and multiple linear models, quantitative predictors showed similar effects over NDVI (compare Figs. 3 and 4). On the other hand, the categorical variable vegetation type appeared as an important variable explaining the ordination of the sites ( $R^2 = 0.16$ ,  $p < 0.001$ , Fig. 3 upper panel), and also in the multiple linear regression models it appeared always with the highest importance when predicting NDVI across all seasons (Fig. 4). This variable eventually contributed to explain the heterogeneity caused by different soil types, species composition and grazing patterns, all related with NDVI. All models showed the lowest goodness of fit for the biomass productivity estimates in late summer (end of the dry season). A possible explanation for the poor fit could be different stocking rates in forest openings in a context of low forage availability at the end of summer, which increases NDVI heterogeneity even further.

The relatively high weight of the landscape variables in predicting NDVI was a novel result. From the six variables with the highest importance after vegetation type (Fig. 4, right) in the linear models, four were regional: precipitation, altitude, slope and aspect, and two were associated with landscape configuration: perimeter/area ratio and form factor. While the importance of regional drivers has been often studied (e.g., Sanaei et al. 2019), our study shows that landscape metrics exhibited also significant correlations with NDVI.

The relationship between NDVI and the six quantitative predicting variables varied throughout the growing period (Fig. 4, right). In spring, water availability generally does not limit vegetation growth in this region, while temperatures are on the rise. The negative effect of altitude over NDVI results from the inverse relationship between temperature and altitude, which leads to slow down vegetation growth and a reduction in photosynthetic activity. Also, the negative effect of opening perimeter/area ratio over spring NDVI implies that wide openings with low canopy border have higher herbaceous and shrub forage

productivity at that date, probably due to less competition for light between forest canopy and grasses (Belsky 1994; Kellas et al. 1995; Baldassini et al. 2018). Conversely, mean annual precipitation, aspect and landscape metrics took higher relevance over the vegetation photosynthetic activity of the openings in summer and late summer. Regionally, this is the period with greater water deficits because of lower precipitations and higher temperatures (Bianchi et al. 2016). In this season, NDVI was higher on more humid hillside orientations (South and Southeast) and when the openings were small or had longer perimeters of canopy border. This last correlation can be probably due to a facilitation effect of trees over vegetation growing inside the opening in dry periods of the year.

Our results are partly confirmed by the findings of other authors. When soil moisture is not a limiting factor, as in early spring, grasses compete mainly for light with surrounding trees (Belsky 1994; Holmgren et al. 1997; Bahamonde et al. 2012). Conversely, when soil water is limiting, as found also by Karki and Goodman (2015), facilitation in small openings or with high tree canopy borders can occur through tree shading. Shading decreases water evaporation losses when temperatures are high, and consequently increases water availability for vegetation growth (Van Miegroet et al. 2010). An alternate hypothesis is facilitation through a reduction in wind speed by trees (Geiger et al. 2009). Wind affects the microclimate of forest openings in multiple ways. The overall effect of a reduction in wind speed might result in a reduction in evapotranspiration along the year. In this way, water availability in summer and late summer will be higher for vegetation growth in small openings or with higher tree borders.

Our findings suggest that a competition process for light between trees and grasses in spring shifts to facilitation in summer, due to changes in soil moisture. Mazía et al. (2016) also found a shift from competition to facilitation with increasing aridity. Similar effects were found in southern Patagonia (Peri et al. 2005, 2016b) but across different spatial circumstances, as in our case the shift was determined by temporal instead of spatial variation. Conversely, Baldassini et al. (2018) found a reduction in grass growing below trees, as a consequence of competition for light even in an arid zone. In their case, however, precipitation events occurred mostly within the

growing period, probably nullifying facilitation effects of trees over grasses.

Predicting overall forage productivity through NDVI remains challenging in forest openings, and the reliability of predictive models depends on forest characteristics (Borowik et al. 2013; Gautam et al. 2019). Despite high values of goodness of fit obtained, linear models presented in this work are only suitable for exploring trends of forage productivity and its relationship with variables of interest. However, the estimation of overall forage productivity in order to calculate carrying capacity should use a more complex analysis, such as an integration NDVI (INDVI) from many dates within the growing period (Pettorelli et al. 2005). Such analysis must be complemented with field measurements of biomass cuts, accessibility, preference, diet selection and nutritious values of forage (Bestelmeyer et al. 2017). This is because preference and diet selection depend on many factors, such as continuous grazing reduces big herbivores preference of species within an area (Forbes et al. 2019; González-Hernández et al. 2020). The methodology presented here sets the basis to collect remote sensing and field data in forest's openings, highlighting the inclusion of landscape configuration in the analysis, in order to achieve a precise estimation of overall forage productivity in target areas. Our study highlights the importance of considering different vegetation types when studying forage productivity in the openings of native forests, something that is not always readily considered in most remote sensing studies.

Our results also indicate that there is an expected variation in vegetation growth in different environments and throughout the year, depending on forest's characteristics. Additionally, they suggest there can be more convenient configurations of shape and size of forest openings depending on whether the objective is to produce forage in spring or in summer. In our study area, large and regularly shaped openings with short perimeters appear to be the most convenient configuration to maximize grassland productivity in early spring. By contrast, small elongated openings or with long borders of tree canopy appear to be the most appropriate design of forest openings when the objective is to produce forage in summer and late summer. Local producers in El Manso and Foyel valleys speak of 'grass drying out' in large openings in summer, an empirical observation that confirms the

trends observed in our analysis. Although our study focuses on North Patagonia forests, the results presented here are potentially relevant to temperate forests worldwide. Yet, effect sizes and significance are likely to be location specific as affected by climate, soil type and vegetation.

## Conclusion

Understanding the dynamics of forage productivity in heterogeneous native forests is key to designing sustainable grazing management schemes. The methodology applied here allowed us to study NDVI of grasslands and shrublands within forest's openings. Potential forage productivity may be explained by the variation in regional environmental drivers such as vegetation type, precipitation, altitude and temperature. Actual forage productivity within forest openings is also affected by the size and shape of such openings, since landscape configuration may regulate microclimatic regimes which may facilitate processes between trees and grasses. A shift from competition in spring to facilitation in the dry summer between trees and grasses growing in these openings is a possible explanation for the seasonal variation observed our study area, to be further tested. Also, an adjusted estimation of overall forage productivity in forest openings with measures along the growing period is possible with this methodology. Finally, this work indicates that landscape patterns must be considered when studying overall forage productivity for cattle grazing in native forests with remote sensors.

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**Availability of data and material** The data that support the findings of this study are available from CNES 2016 & 2017, reproduced by CONAE under Spot Image/AIRBUS license, but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Rest of data are published and available from the authors upon reasonable request (see Online Resource 2).

**Code availability** We used software applications QGIS3.8©, ENVI 5.3© and R3.5.2©.

#### Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

#### References

- Anderson D, Sweeney D, Williams T (2012) Estadística para negocios y economía, 11a edn. México, D.F
- Bahamonde HA, Peri PL, Álvarez R, Barneix A (2012) Producción y calidad de gramíneas en un gradiente de calidades de sitio y coberturas en bosques de *Nothofagus antarctica* (G. Forster) Oerst. en Patagonia. *Asociación Argentina de Ecología; Ecología Austral* 22(1):62–73
- Baldassini P, Despósito C, Piñeiro G, Paruelo JM (2018) Silvopastoral systems of the Chaco forests: effects of trees on grass growth. *J Arid Environ* 156:87–95. <https://doi.org/10.1016/j.jaridenv.2018.05.008>
- Belsky AJ (1994) Influences of trees on savanna productivity: tests of shade, nutrients, and tree-grass competition. *Ecology* 75:922–932. <https://doi.org/10.2307/1939416>
- Bestelmeyer BT, Andrew Ash, Brown JR et al (2017) Rangeland systems
- Bestelmeyer BT, Brown JR, Havstad KM et al (2003) Development and use of state-and-transition models for rangelands. *J Range Manag* 56:114–126
- Bianchi E, Villalba R, Viale M et al (2016) New precipitation and temperature grids for northern Patagonia: advances in relation to global climate grids. *J Meteorol Res* 30:38–52 (2016). <https://doi.org/10.1007/s13351-015-5058-y>
- Borowik T, Pettorelli N, Sönnichsen L, Jędrzejewska B (2013) Normalized difference vegetation index (NDVI) as a predictor of forage availability for ungulates in forest and field habitats. *Eur J Wildl Res* 59:675–682. <https://doi.org/10.1007/s10344-013-0720-0>
- Briske DD, Fuhlendorf SD, Smeins FE (2005) State-and-transition models, thresholds, and rangeland health: a synthesis of ecological concepts and perspectives. *Rangel Ecol Manag* 58:1–10. [https://doi.org/10.2111/1551-5028\(2005\)58%3c1:SMTARH%3e2.0.CO;2](https://doi.org/10.2111/1551-5028(2005)58%3c1:SMTARH%3e2.0.CO;2)
- Bussoni A, Alvarez J, Cubbage F et al (2019) Diverse strategies for integration of forestry and livestock production. *Agrofor Syst* 93:333–344. <https://doi.org/10.1007/s10457-017-0092-7>
- Bustos C (1995) El clima en el valle del Río Manso Inferior (Río Negro). 12
- Cameron M (2016) Cows and clearcutting: how can we manage both in an aspen forest? En: 10th International Rangeland Congress. p 265
- Chen J, Saunders SC, Crow TR et al (1999) Microclimate in forest ecosystem and landscape ecology—variations in local climate can be used to monitor and compare the effects of different management regimes. *Bioscience* 49:288–297. <https://doi.org/10.2307/1313612>
- De Araújo RA, Rodrigues RC, Costa S et al (2016) Forage intake and performance of cattle in silvo-pastoral systems and monoculture of Marandu in Pre-Amazon region. *African J Agri Res* 11:1849–1857. <https://doi.org/10.5897/AJAR2016.10795>
- Easdale MH, Aguiar MR (2012) Regional forage production assessment in arid and semi-arid rangelands—a step towards social-ecological analysis. *J Arid Environ* 83:35–44. <https://doi.org/10.1016/j.jaridenv.2012.03.002>
- Ergon SG, Korhonen P et al (2018) How can forage production in Nordic and Mediterranean Europe adapt to the challenges and opportunities arising from climate change? *Eur J Agron* 92:97–106. <https://doi.org/10.1016/j.eja.2017.09.016>
- Feng FL, Wu CC (2018) Development and validation of ecological site quality model: an example of *Chamaecyparis formosensis* in Taiwan. *J For Plann* 22(2): 77–83. [https://doi.org/10.20659/jfp.22.2\\_77](https://doi.org/10.20659/jfp.22.2_77)
- Forbes ES, Cushman JH, Burkepile DE, Young TP, Klope M, Young HS (2019) Synthesizing the effects of large, wild herbivore exclusion on ecosystem function. *Funct Ecol* 33:1597–1610
- Garibaldi LA, Aristimuño FJ, Oddi FJ, Tiribelli F (2017) Inferencia multimodelo en ciencias sociales y ambientales. *Ecol Austral* 348–363. <https://doi.org/10.25260/EA.17.27.3.0.513>
- Garibaldi LA, Oddi FJ, Aristimuño FJ, Behnisch AN (2019) Modelos estadísticos en lenguaje R. San Carlos de Bariloche
- Garrouette EL, Hansen AJ, Lawrence RL (2016) Using NDVI and EVI to map spatiotemporal variation in the biomass and quality of forage for migratory elk in the Greater Yellowstone Ecosystem. *Remote Sens*. <https://doi.org/10.3390/rs8050404>
- Gautam H, Arulmalar E, Kulkarni MR, Vidya TNC (2019) NDVI is not reliable as a surrogate of forage abundance for a large herbivore in tropical forest habitat. *Biotropica* 51:443–456. <https://doi.org/10.1111/btp.12651>
- Geiger R, Aron RH, Todhunter P (2009) The climate near the ground. Rowman & Littlefield
- Godagnone R, Bran DE (2009) Inventario integrado de los recursos naturales de la provincia de Río Negro. Ediciones INTA
- Golluscio RA (2009) Receptividad ganadera: marco teórico y aplicaciones prácticas. *Ecol Austral* 19:215–232
- González-Hernández MP, Mouronte V, Romero R et al (2020) Plant diversity and botanical composition in an Atlantic heather-gorse dominated understory after horse grazing suspension: comparison of a continuous and rotational management. *Glob Ecol Conserv* 23. <https://doi.org/10.1016/j.gecco.2020.e01134>
- Greenberg CH, Perry RW, Harper CA et al (2011) The role of young, recently disturbed upland hardwood forest as high

- quality food patches. n: Sustaining Young Forest Communities. Springer, pp 121–141
- Hanna MM, Steyn-Ross DA, Steyn-Ross M (1999) Estimating biomass for New Zealand pasture using optical remote sensing techniques. *Geocarto Int* 14:89–94. <https://doi.org/10.1080/10106049908542121>
- Holmgren M, Scheffer M, Huston MA (1997) The interplay of facilitation and competition in plant communities. *America (NY)* 78:1966–1975. <https://doi.org/10.2307/2265937>
- Iglay RB, Conkling TJ, DeVault TL et al (2019) Forage or biofuel: assessing native warm-season grass production among seed mixes and harvest frequencies within a wild-life conservation framework. *Southeast Nat* 18:1. <https://doi.org/10.1656/058.018.0103>
- Karki U, Goodman MS (2015) Microclimatic differences between mature loblolly-pine silvopasture and open-pasture. *Agrofor Syst* 89:319–325. <https://doi.org/10.1007/s10457-014-9768-4>
- Kellas JD, Bird PR, Cumming KN et al (1995) Animal production under a series of *Pinus radiata*-pasture agroforestry systems in South-West Victoria, Australia. *Aust J Agric Res* 46:1299–1310. <https://doi.org/10.1071/AR951299>
- La Manna L, Collantes M, Bava J, Rajchenberg M (2008) Seedling recruitment of *Austrocedrus chilensis* in relation to cattle use, microsite environment and forest disease. *Ecol Austral* 18(01):027–041
- Licata JA, Gyenge JE, Fernández ME et al (2008) Increased water use by ponderosa pine plantations in northwestern Patagonia, Argentina compared with native forest vegetation. *For Ecol Manage* 255:753–764. <https://doi.org/10.1016/j.foreco.2007.09.061>
- Ludewig K, Donath TW, Zelle B et al (2015) Effects of reduced summer precipitation on productivity and forage quality of floodplain meadows at the Elbe and the Rhine River. *PLoS One*. <https://doi.org/10.1371/journal.pone.0124140>
- Marsaglia G, Tsang WW, Wang J (2003) Evaluating Kolmogorov's distribution. *J Stat Softw* 8:1–4. <https://doi.org/10.18637/jss.v008.i18>
- Martinez-Meier A, Fernández ME, Dalla-Salda G et al (2015) Ecophysiological basis of wood formation in ponderosa pine: Linking water flux patterns with wood microdensity variables. *For Ecol Manage* 346:31–40. <https://doi.org/10.1016/j.foreco.2015.02.021>
- Masters RE, Lochmiller RL, Engle DM (1999) Effects of timber harvest and prescribed fire on white-tailed deer forage production. *NCASI Tech Bull* 21:327–328
- Maurer T (2013) How to pan-sharpen images using the Gram-Schmidt pan-sharpen method &ndash; a recipe. *ISPRS Int Arch Photogramm Remote Sens Spat Inf Sci* 239–244. <https://doi.org/10.5194/isprsarchives-xxl-1-w1-239-2013>
- Mazía N, Moyano J, Perez L et al (2016) The sign and magnitude of tree–grass interaction along a global environmental gradient. *Glob Ecol Biogeogr* 25:1510–1519. <https://doi.org/10.1111/geb.12518>
- Murgueitio E (2005) *Silvopastoral systems in the neotropics*. Int Silvopastoral Sustain L Manag CAB Lugo, España 24–29
- Oksanen J (2015) *Multivariate analysis of ecological communities in R: Vegan Tutorial*
- Özcan M, Gökbulak F (2017) Vegetation characteristics of forest gaps in yuvacik watershed, Izmit/Turkey
- Peri PL, Dube F, Varella A (2016a) Silvopastoral systems in Southern South America. <https://doi.org/10.1007/978-3-319-24109-8>
- Peri PL, Hansen NE, Bahamonde HA et al (2016b) Silvopastoral systems under native forest in patagonia Argentina. In: *Silvopastoral systems in Southern South America*, pp 117–168. [https://doi.org/10.1007/978-3-319-24109-8\\_6](https://doi.org/10.1007/978-3-319-24109-8_6)
- Peri PL, Sturzenbaum MV, Monelos L et al (2005) Productividad de sistemas silvopastoriles en bosques nativos de ñire (*Nothofagus antarctica*) de Patagonia Austral. *Terc Congr For Argentino y Latinoam* 1–10
- Peringer A, Schulze KA, Stupariu I et al (2016) Multi-scale feedbacks between tree regeneration traits and herbivore behavior explain the structure of pasture-woodland mosaics. *Landsc Ecol* 31:913–927. <https://doi.org/10.1007/s10980-015-0308-z>
- Perry DA (1994) *Forest ecosystems*. The Johns, Maryland
- Pettorelli N, Vik JO, Mysterud A et al (2005) Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends Ecol Evol* 20:503–510. <https://doi.org/10.1016/j.tree.2005.05.011>
- Piazza MV, Garibaldi LA, Kitzberger T, Chaneton EJ (2016) Impact of introduced herbivores on understory vegetation along a regional moisture gradient in Patagonian beech forests. *For Ecol Manage* 366:11–22
- Postadjian T, Le Bris A, Sahbi H, Mallet C (2017) Investigating the potential of deep neural networks for large-scale classification of very high resolution satellite images. *ISPRS Ann Photogramm Remote Sens Spat Inf Sci* 4:183–190. <https://doi.org/10.5194/isprs-annals-IV-1-W1-183-2017>
- Robinson NP, Jones MO, Moreno A et al (2019) Rangeland productivity partitioned to sub-pixel plant functional types. *Remote Sens* 11:1–9. <https://doi.org/10.3390/rs11121427>
- Rusch VE, Cavallero L, López DR, Rusch VE, Cavallero L, López DR, Rusch VE, Cavallero L (2016) El Modelo De Estados Y Transiciones Como Herramienta Para La Aplicación De La Ley 26331. *Patagonia Forestal* 1:20–27
- Sanaei A, Li M, Ali A (2019) Topography, grazing, and soil textures control over rangelands' vegetation quantity and quality. *Sci Total Environ* 697:134153. <https://doi.org/10.1016/j.scitotenv.2019.134153>
- SAyDS & CIEFAP (2016) *Actualización de la Clasificación de Tipos Forestales y Cobertura del Suelo de la Región Bosque Andino Patagónico*. Informe Final. CIEFAP.
- SIPHN (2019) *Base de Datos Hidrológica Integrada*. <https://www.argentina.gob.ar/obras-publicas/hidricas/base-de-datos-hidrologica-integrada>
- Thompson MW, Shaw MG, Umber RW, Skeen, JE, Thackston RE (1991) Effects of herbicides and burning on overstory defoliation and deer forage production. *Wildlife Society Bulletin* (1973–2006) 19(2):163–170. <http://www.jstor.org/stable/3782324>
- Van Miegroet H, Hysell MT, Johnson AD (2010) Soil microclimate and chemistry of spruce-fir tree Islands in Northern Utah. *Soil Sci Soc Am J* 64:1515. <https://doi.org/10.2136/sssaj2000.6441515x>
- Wangchuk K, Darabant A, Gratzner G, Wurzinger M, Zollitsch W (2015) Forage yield and cattle carrying capacity differ by understory type in conifer forest gaps. *Livestock Sci* 180:226–232. <https://doi.org/10.1016/j.livsci.2015.08.003>

Yu X, Zhang M, Yang H, Chen C (2020) An NFI-based site quality evaluation of Chinese fir plantation. *J Sustain for* 39(2):137–152. <https://doi.org/10.1080/10549811.2019.1623051>

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