Measuring forest fragmentation using multitemporal remotely sensed data: three decades of change in the dry Chaco

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Abstract

We introduce an approach based on remotely sensed data to summarize forest fragmentation over time, which specifically accounts for the interdependencies between landscape composition and configuration changes. The proposed method consists of five steps: i) multitemporal landscape sampling, ii) calculation of selected landscape pattern indices, iii) statistical comparison, iv) construction of sampled-based relationship spaces, and v) trajectory analysis. To show how the proposed method works in practice we examined the multitemporal fragmentation of the Arid Chaco forest in central Argentina during the period 1979-2010 using forest maps derived from Landsat images. As shown by our results, the approach provides a consistent framework for the interpretation of landscape structural changes over time.

Keywords: Chaco dry forests, forest loss, Landsat, landscape metrics, sample-based analysis, trajectory analysis.

Introduction

Forest ecosystems have played a major role in human history and forest fragmentation has accompanied population growth and development throughout the world for thousands of years [FAO, 2012]. Forest fragmentation is a landscape-level process in which a large intact forest area is progressively divided into smaller, geometrically altered and isolated patches [Forman and Godron, 1986; Fahrig, 2003]. Anthropogenic fragmentation of natural forests constitutes one of the most severe causes of biodiversity loss [Foley et al., 2005; Wade

et al., 2003] and of the impairment of forest ecosystem services [Marchetti et al., 2012; Gamefeldt et al., 2013]. The remarkable speed of forest fragmentation all over the world urges to find standard screening procedures able to stress the benefits and drawbacks of different management scenarios [Gamefeldt et al., 2013]. Scientifically sound instruments able to describe and monitor forest fragmentation are crucial for determining conservation priorities aimed at guaranteeing forest biodiversity and ecosystem services over time [Gomez-Sanz et al., 2008].

Remotely sensed imagery is the most successful tool for forest cover monitoring, as it offers a cost-effective option for frequent observations of vast areas [Potapov et al., 2012]. Moreover, remote sensing is particularly effective for producing forest cover maps (for a throughout review see Achard and Hansen [2012]). Forest maps provide explicit information on forest distribution [Stehman, 2012], which is the first step of fragmentation analysis.

Forest, fragmentation consists of two interdependent components: forest loss and changes in spatial configuration [Neel et al., 2004; Long et al., 2010]. Accordingly, a proper interpretation of forest fragmentation needs to consider the interdependencies among these aspects [Neel et al., 2004]. Indeed, while the reduction of forest cover is usually accompanied by a change in the spatial configuration of the remaining forest fragments, a large body of class-level configuration metrics (hereafter referred to as LPIs) [McGarigal and Marks, 1995] is highly correlated with habitat abundance [Neel et al., 2004; Cushman and McGarigal, 2007]. In order to investigate the nonlinear and non-monotonic relationship between habitat cover and LPIs in deeper detail, Long et al. [2010] proposed the use of specific bidimensional 'relationship spaces' in which the variation of LPIs, such as forest fragmentation, can be plotted against different levels of class proportions (i.e. forest cover). In their seminal paper, Long et al. [2010] used neutral simulation models to reproduce the relationship between pattern metrics and habitat proportions. However, due to their intrinsically random nature, neutral simulation models are usually unable to reproduce the fragmentation patterns of highly disturbed landscapes where the anthropogenic forces give rise to severely constrained spatial distributions [Li et al., 2004]. In this context, the use of sample data obtained from remotely sensed imagery may represent a valuable alternative. For instance, by projecting the LPI values measured on sample data in a bidimensional relationship space it is possible to depict the observed real-world association between habitat cover and configuration metrics of a given landscape at a given point in time.

The aim of this paper is thus to propose an approach based on remotely sensed data to summarize forest fragmentation over time, which specifically accounts for the interdependencies between landscape composition and configuration changes. In particular, we suggest to quantify changes in forest loss and spatial configuration using random sampling of multi-temporal maps followed by a bootstrapping significance test. As an application for demonstration, a multi-temporal analysis of forest fragmentation in the Argentinean dry Chaco is performed.

Analyzing forest fragmentation over time

The proposed approach for assessing forest fragmentation over time can be described in five steps: i) multitemporal landscape sampling, ii) LPIs selection and calculation, iii) statistical comparison, iv) construction of the sampled-based relationship spaces and v) multitemporal trajectory analysis of the LPIs estimators.

(i) Multitemporal landscape sampling

The application of sampling methods for analyzing landscape-scale forest configuration may yield significant cost savings and more accurate results when the analyzed area is extensive [Ramezani et al., 2013]. The sample-based method consists in sampling the study area with the objective of achieving approximately what would happen if the classical wall-to-wall data were analyzed [Stehman, 2012]. In its very essence, for fragmentation analysis, we propose to extract randomly a finite population of n sampling units from a grid of N non-overlapping cells (e.g. 1 km × 1 km or 10 km × 10 km units) in which the study area is partitioned. For a review of the strengths and weaknesses of coarse-scale sample-based methods for forest monitoring see Stehman [2012].

(ii) LPI selection and calculation

Partitioning a region into spatial units and then selecting a subset of these units introduces artificial patch edge and patch truncation effects that may lead to biased sample-based estimators of landscape pattern metrics [Hassett et al., 2012]. Only a limited set of LPIs are adequate for sample-based analysis of landscape structure [Hassett et al., 2012; Ramezani et al., 2013]. In particular, the sample-based analysis of the percent cover of a given landscape class and of its edge density offers unbiased estimators of the entire landscape [Stehman et al., 2003], while the bias of the estimators of mean patch size and patch density is very small or negligible [Hassett et al., 2012]. All those parameters, which are also among the most used indicators for fragmentation analysis [Townsend et al., 2009; Moreno-Sanchez et al., 2012; Frate et al., 2014], can be easily calculated for each sampling unit using off-the-shelf software, such as FRAGSTATS [McGarigal and Marks, 1995].

(iii) LPIs estimation and statistical comparison

Once the fragmentation LPIs of each sampling unit have been calculated, a variety of estimators can be used to assess the parameter of interest. For probability sampling designs and design-based inference, a general unbiased estimator of a population total is the Horvitz-Thompson estimator [Overton and Stehman, 1995]. Imagine a landscape that is entirely tessellated into N non-overlapping units, and let θ denote the value of a landscape pattern metric computed from complete wall-to-wall land cover data for the region of interest and θ* the mean value of the metric for the universe N. The Horvitz-Thompson estimator allows to construct an unbiased estimator $\widehat{\theta}^*$ for any probability sampling design of n units out of N. An important advantage of the Horvitz-Thompson estimator is that for the special cases of the basic sampling designs typically used in practice (e.g. simple random sampling, systematic sampling, or stratified random sampling), the Horvitz-Thompson estimator reduces to simplified formulas. For instance, for a simple random sampling design the estimator reduces to the arithmetic mean of the n sampling units:

$$\widehat{\theta}^* = 1/n \sum_{1}^{n} z_n \quad [1]$$

where Z_n is the value of the metric computed for the n-th sampling unit. For a detailed description of the Horvitz-Thompson estimator for probability sampling designs and

design-based inference see Stehman [2012]. As a next step, to test for differences among landscape metrics of fragmentation, bootstrap procedures [Manly, 2006; Fortin et al., 2012) can be used.

(iv) Construction of the sample-based relationship space
To visualize the nonlinear relationship between forest cover and landscape metrics, the index values of all sampled spatial units can be projected against the corresponding forest cover proportions in order to build index-specific relationship spaces [sensu Long et al., 2010]. Such relationship spaces not only provide a sound frame for the analysis of fragmentation over time but are also useful for describing the spatial consequences of forest loss.

(v) Trajectory analysis
Landscape trajectory analysis, introduced by Cushman and McGarigal [2007], consists in describing the position of a given landscape over two or more observation periods in the corresponding multidimensional LPI space. Here, we propose to perform trajectory analysis in the index-specific bidimensional relationship space of Long et al. [2010] to provide an intuitive and interpretable description of forest fragmentation over time. Once the LPIs estimators of a number of observation periods are plotted in sample-based relationship space, temporal trajectories can be drawn connecting the corresponding point as time-ordered series. When, temporal changes are moderate, the fragmentation estimators are located very close in the relationship space. To the contrary, in highly dynamic landscapes, the position of the fragmentation estimators in the relationship space tends to diverge over time.

Worked example
Study area
A test site of roughly 2713 km^2 of the Gran Chaco dry forest located in central Argentina was selected for the analysis (Fig. 1). The climate is warm temperate to subtropical, with a mean annual temperature ranging from 16°C to 19°C and mean annual rainfall ranging from 400 to 800 mm [Zak et al., 2008]. The Gran Chaco, is one of largest seasonally dry subtropical forests in the world (ca. 1200000 km^2) and comprises wide areas in Argentina, Paraguay and Bolivia where the transition between the tropics and the temperate belt does not occur in the form of a desert but as semi-arid forests and woodlands [Morello and Adamoli, 1974; Zak et al., 2008]. The study area was formerly dominated by *Aspidosperma quebracho-blanco and Schinopsis marginata* subtropical seasonally dry forests [Sayago, 1969; Zak and Cabido, 2002]. Despite many outstanding features in terms of biodiversity values [Molina et al., 1999; Cagnolo et al., 2006; Torrella et al., 2013] and ecosystem services [Conti and Diaz, 2013; Cáceres, 2014], which make these complex ecosystems worthy of protection, the Gran Chaco, is one of the main deforestation areas of Latin America [Grau and Aide, 2008; Hansen et al., 2012]. During the last three decades the generalized expansion of agriculture [Zak et al., 2008; Hoyos et al., 2013], driven by global trends in technology and soybean markets [Grau et al., 2005], but also by global changes in the precipitation regimes [Hoyos et al., 2013], have promoted a sharp drop of the Gran Chaco natural forests.
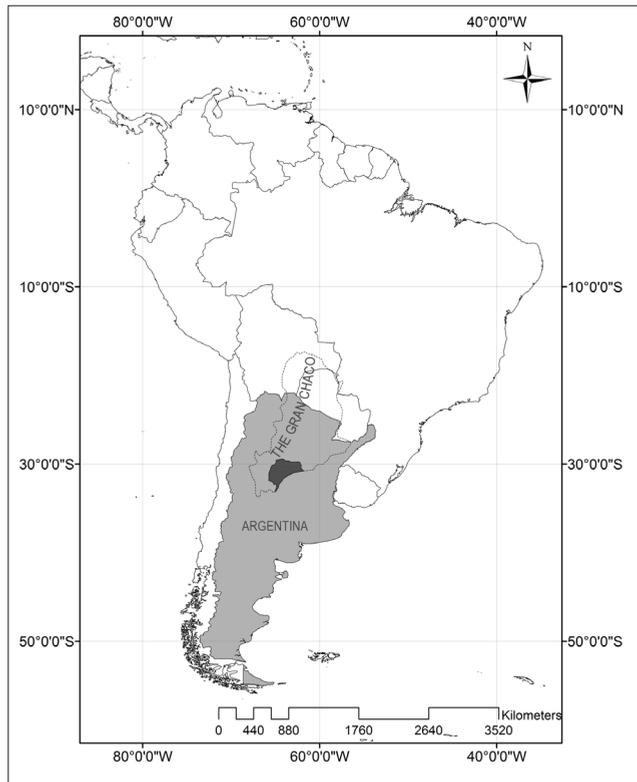
Figure 1 - Location of the study area (in dark grey). The Gran Chaco biogeographical region (black-dashed line) and the administrative limits of Argentina (light grey) area also shown.

Methods

Based on Landsat satellite images for the years 1979, 1999 and 2010 and extensive field work three large-scale land cover maps for the study area were produced. To identify the land-cover units, three Landsat MSS scenes from February 1979, three Landst TM scenes from November 1999, and three Landsat TM scenes from March 2010 were used. All Landsat images were acquired during the vegetation growing season of the southern Hemisphere. The classification of Landsat MSS and TM images resulted in reliable land-cover maps (overall accuracy 80%) composed of five vegetation classes: closed forest, open forest, shrublands, halophytic vegetation and cultural vegetation (croplands and urban areas). For a detailed description of the classification procedure, see Hoyos et al. [2013].

The subsequent fragmentation analysis was performed solely on the closed forests class. These forests correspond to lowland seasonally dry forests, with Aspidosperma quebracho-blanco and Schinopsis lorentzii as dominant trees and a canopy cover of at least 50% [Cabido et al., 1992; Zak and Cabido, 2002]. A set of non-overlapping square grid units was randomly sampled without replacement from the tessellated study area (roughly amounting to 10% of the total extent of the analyzed land cover class). The analysis was performed at two grid dimensions [see Long et al., 2010], comparable with those commonly used for

mid-scale and coarse-scale regional forest monitoring [Wulder et al., 2008]: 1 km² (1692 sampling units) and 10 km² (191 sampling units). For each sampling unit, a set of four indices of landscape fragmentation was computed with FRAGSTATS [McGarigal and Marks, 1995]. These indices include: percent of forest cover (% Forest), edge density (ED; m/ha), mean patch size (MPS; ha) and patch density (PD; number of patches/ha). The detailed formulas of the LPIs used in this paper can be found in McGarigal and Marks [1995]. For each grid size three index-specific relationship spaces were built by projecting the values of ED, PD and MPS computed for each sampling unit against the corresponding forest cover values. The Horvitz-Thompson estimators of all LPIs were then calculated as the arithmetic mean of the n cells sampled at each date. The LPI estimators were finally plotted in the corresponding sample-based relationship spaces to describe the temporal trajectory of each index. Temporal differences between the LPI estimators were statistically tested with a bias-corrected and accelerated bootstrap procedure [Manly, 2006; Fortin et al., 2012].

Results

The sample-based analysis of the Arid Chaco forest over time underlines a consistent process of fragmentation. The LPI temporal trajectories in relationship space for both grid dimensions are shown in Figure 2 and Table 1. During the last 30 years, a significant decline of forest cover and a consistent change in forest spatial configuration can be observed. As shown in Table 1, the results obtained for the 1 km² grid are very similar in sign and strength to the results of the 10 km² grid. Therefore, for simplicity, in this section we report only the LPI values associated to the smaller grid size.

Table 1 - Horvitz-Thompson estimators of the sample-based LPIs used in this study for the years 1979, 1999 and 2010 and for two grid sizes: 1 km2 and 10 km2. The 99% confidence intervals obtained by the bias-corrected and accelerated bootstrap procedure are also shown. Different lowercase letters on the right side of the index mean values show significant pairwise differences between the observation periods at p = 0.01. PLAND: percentage of forest cover (%), MPS: mean patch size (ha), ED: edge forest density (m/ha), PD: patch density (number of patches/ha).

		1979			1999			2010		
		Mean	Lower CI	Upper CI	Mean	Lower CI	Upper CI	Mean	Lower CI	Upper CI
1 km²	PLAND	31.20 [a]	30.03	32.39	23.29 [b]	21.90	24.66	4.19 [c]	3.77	4.63
	MPS	13.98 [a]	12.81	15.14	12.72 [a]	11.53	14.01	0.79 [b]	0.61	0.98
	ED	60.75 [a]	59.21	62.25	39.06 [b]	37.25	40.89	15.63 [c]	14.33	16.89
	PD	6.00 [a]	5.82	6.19	3.76 [b]	3.57	3.94	3.22 [c]	3.00	3.45
		1979			1999			2010		
10 km²	PLAND	33.55 [a]	30.44	36.74	23.82 [b]	20.36	27.44	3.48 [c]	2.68	4.30
	MPS	62.22 [a]	38.42	87.91	32.77 [a]	16.93	50.35	0.70 [b]	0.58	0.83
	ED	64.74 [a]	61.09	68.60	41.79 [b]	37.02	46.68	14.29 [c]	11.48	17.11
	PD	4.19 [a]	3.83	4.53	2.64 [b]	2.33	2.96	2.77 [b]	2.30	3.26

Forest cover consistently declined from roughly 31% of the 1979 landscape to ~ 4% in 2010. Forest loss occurred at different rates during the analyzed time period. In the first

two decades (1979-1999) forest cover decreased from ~31% to ~ 23%, while in the last ten years (1999-2010), a much larger forest loss (from ~23% to ~ 4%) was observed. At the same time, fragmentation metrics are characterized by index-specific behaviors in relation to forest cover (Fig. 2). For instance, as shown by the relationship space of MPS vs. % Forest (Fig. 2), mean patch size tends to be very low for forest cover values below 50%; higher MPS values are observed only for forest cover values > 50%.
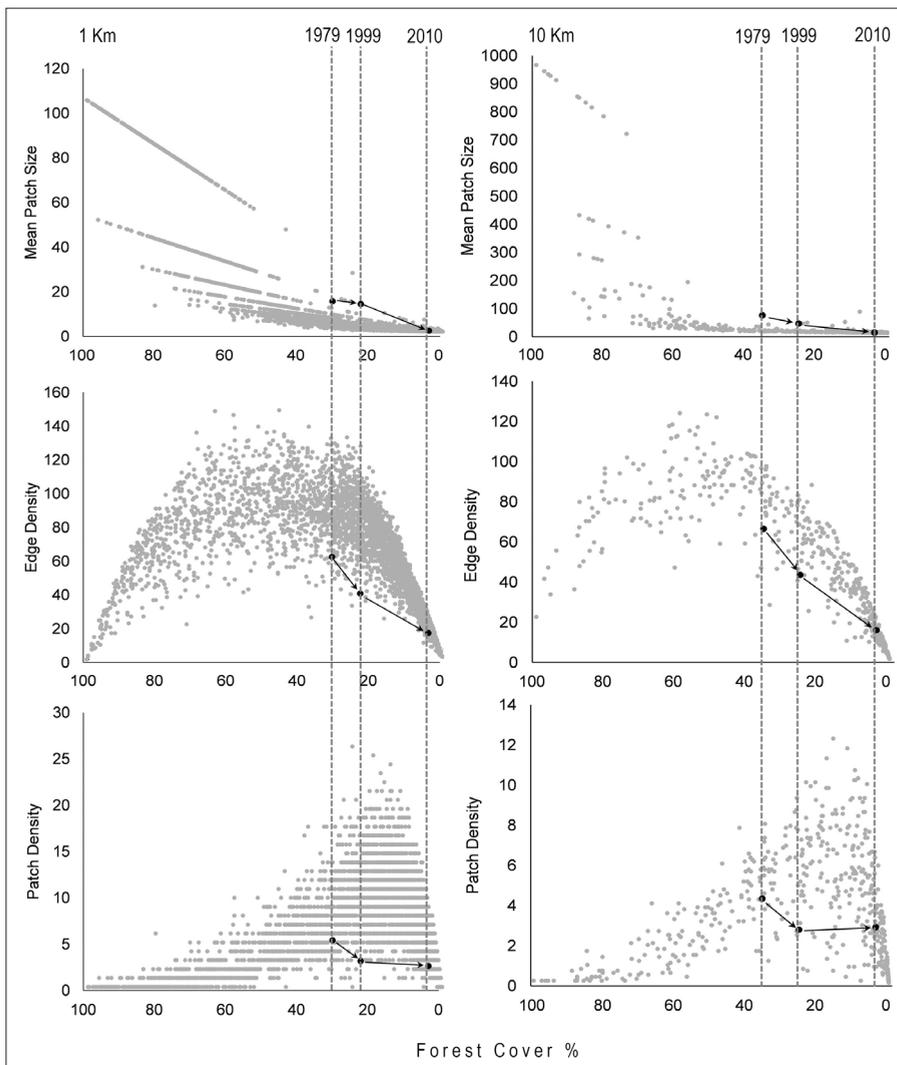
Figure 2 - Trajectory analysis of the Chaco dry forests trough the years 1979, 1999 and 2010 in the relationship spaces given by the LPI values vs. forest cover. MPS: mean patch size (ha), ED: edge forest density (m/ha), PD: patch density (number of patches/ha). Grey circles represent the LPI values of all square grids sampled in the tree years of observation. Black circles are the Horvitz-Thompson estimators of each index for each year of observation. Solid lines indicate the trajectories between successive dates.

The multitemporal analysis of the mean MPS values highlights significant changes in the 1999-2010 period (MPS ranges from 12.72 in 1999 to 0.79 in 2010; p = 0.01), whereas no significant changes were observed in the 1979-1999 period. Therefore, although MPS is among the most commonly used parameters for a wide range of landscape-level applications [e.g. Batistella et al., 2003; Fahrig, 2003; Frohn and Hao, 2006], our results are consistent with previous studies of Neel et al. [2004], which considered MPS as a parameter of little use for highlighting structural differences among landscapes with comparable cover values, especially at low cover levels.

As shown in Figure 2, Edge density is characterized by a parabolic relationship with forest cover. ED is low at very high and very low forest cover values and peaks at intermediate values of forests cover. The ED estimators for the years 1979, 1999 and 2010 show a significant, decline over time, ranging from 60.75 in 1979 to 15.63 in 2010. Overall, ED is a widely used parameter for fragmentation analysis, especially for the ecological implications of 'edge effects' [Saura and Martinez-Millan, 2001]. In this view, our results highlight the effectiveness of this index for comparing structural changes in highly fragmented landscapes of low forest cover, such as the Arid Chaco.

Finally, patch density also shows an (asymmetric) parabolic distribution in the corresponding relationship space with peaking values around 20% of forests cover (Fig. 2). The index estimators for the period 1979-1999 show a significant reduction in the number of forest patches (from an average of 6 patches/ha in 1979 to 3.76 patches/ha in 1999; p = 0.01). After this date, mean patch density remained more or less constant, although forest cover decreased from ~23% to ~ 4%.

Discussions

In this paper, we outlined the recent history of forest cover change in the study area of the Gran Chaco. The results of the fragmentation analysis clearly depict a devastating situation of these dry forests and its progressive reduction to few small fragments during the last decades. The forest landscape changed significantly between 1979 and 2010 and deforestation processes are probably still active. A thorough discussion of the ecological consequences of the observed forest loss is beyond the scope of this paper, but see Grau et al. [2005], Zak et al. [2008], Caldas et al. [2013], Hoyos et al. [2013] for details.

From a more general viewpoint, our findings underline the potential role of sample-based relationship spaces for fragmentation analysis. The proposed approach effectively describes the relationship between forest loss and landscape structural changes and offers a sound framework for a correct interpretation of forest fragmentation processes, while the high number of replicates enables the calculation of reliable confidence intervals and hence the statistical comparison between multitemporal maps.

The decreasing trend of mean patch size (MPS) as a function of forest loss, renders MPS an effective metric for describing changes in fragmentation pressure. To the contrary, the parabolic relationship of patch density (PD) and edge density (ED) with forest cover, limits their diagnostic potential to landscapes where forest cover are comprised within certain abundance ranges. Overall, while there are no perfect metrics for fragmentation analysis, many fragmentation indices might be useful under certain conditions and for answering specific biological questions. In this view, our findings suggest to carefully investigate the relationships between configuration metrics and forest cover, paying particular attention to

their nonlinear behavior.

From an applied perspective, the construction of sample-based relationship spaces provides valuable information for land management and fragmentation prevention issues. For instance, efficient conservation programs of forest biodiversity in changing landscapes could benefit from a multitemporal landscape trajectory analysis. Being based on remotely sensed data, the proposed procedure has a strong potential for performing continuous monitoring of landscape fragmentation in an efficient and affordable manner. For instance Earth observation satellites, such as Landsat, SPOT or MODIS, already support many landscape ecological studies from local to global scales at moderate cost [Townsend et al., 2009; Achard and Hansen, 2012; Fichera et al., 2012; Gargano et al., 2012; Schucknecht et al., 2013; Almeida et al., 2014]. Bearing this in mind, we hope our approach will be useful for providing early-warning signals of potential threats to forest integrity and sustainability at increasingly larger scales.

Acknowledgements

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