To link to this article : DOI : 10.1007/BF02093740
URL : http://dx.doi.org/10.1007/BF02093740

To cite this version : Metzger, Jean-Paul and Muller, Etienne *Characterizing the complexity of landscape boundaries by remote sensing.* (1996) Landscape Ecology, vol.11, n° 2, pp. 65-77. ISSN 0921-2973

Characterizing the complexity of landscape boundaries by remote sensing

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Keywords: boundary, covert, landscape indices, landscape physiognomy, fragmentation, diversity, remote sensing

Abstract

This paper presents a method for characterizing the complexity of landscape boundaries by remote sensing. This characterization is supported by a new boundary typology, that takes into account points where three or more landcovers converge (*i.e.,* convergency points or coverts). Landscape boundary richness and diversity indices were proposed and calculated over 19 landscapes in South-East Brazil. Results showed that landscape boundaries, especially convergency points, provided an enrichment in landscape pattern analysis. Landcover boundary diversities were significantly related to landcover shape: elongated riparian units had the highest values for boundary diversity and coverts proportion indices. On the other hand, landscape analysis showed that indices of shape, richness, diversity and coverts proportion provided an additional evaluation of landcover spatial distribution within the landscape.

1. Introduction

Boundaries, defined as transition zones between landscape units (*e.g.,* ecosystems, landcovers or landuses), have been shown to play an important role in the dynamics and functioning of landscapes (Forman and Godron 1981, 1986; Wiens et al. 1985, 1993; Holland 1988; Holland et al. 1991; Naiman et *al.* 1988; Naiman and Décamps 1990). Particularly, boundaries can act as semipermeable membranes, controling biotic and abiotic flows (Wiens *et al.* 1985; Pinay and Décamps 1988), and affect the species composition and diversity, acting in the balance between edge species and core area species (Lovejoy *et al.* 1986; Hansen and di Castri 1992; Décamps and Tabacchi 1994; Tabacchi 1995). Boundary frequency and type also have been used for quantitative descriptions of landscape patterns, as in the case of the patchiness index (Romme 1982), the landscape contagion index (Li and Reynolds 1993) and several fragmentation indices (Li *et al.* 1993; Zipperer 1993).

Two approaches are often used to detect boundaries from a digital analysis of satellite imagery. In the first approach, continuous variables are used and boundaries are placed where the variables show an important rate of change (Fortin 1994). It is then possible to quantify a degree of landscape heterogeneity and boundary widths. However, it is not possible to elaborate a true typology of boundaries as the analysis is limited to only one parameter, generally a vegetation index (*e.g.,* red to infrared spectral band ratio) whose variations are difficult to class.

In the second approach, discrete units are used and boundaries are defined as limits of homogeneous areas (Johnston and Bonde 1989; Johnston *et al.* 1991), and can be characterized by two adjacent classes. A typology of the boundaries is defined according to the adjacent units in contact. However, a first limitation is that the boundary width remains arbitrarily constant across the landscape, and a second one is that the typology bears on only two units contact. The coverts (Harris and Kangas 1979), *i.e.* the points where three or more units converge, are not identified despite their importance for wildlife in concentrating diverse resources and in acting like key points for biological movements in landscape (Harris and Kangas 1979; Forman and Godron 1986).

The objectives of this study were (1) to remove this last limitation by proposing a typology of boundaries that include convergency points and (2) to propose complexity indices for boundary quantitative characterization. Boundary complexity is defined by the number of landscape units that participate in boundary type definitions and by the richness and the area diversity of boundary types.

Proposed approaches were applied to 19 landscapes in the southeastern part of Brazil. This case study was used to discuss the spatial informations and the ecological issues of boundary types and complexity indices.

2. Methods

When analysing boundaries in landscapes, several questions arise. What is the extent of a landscape? What landscape units should be analysed? What precision is required? Meijerink (1985) considered that watersheds were the best units in which the interactions of human and natural resources, and the geographical distribution of their consequences could be observed and modeled. For this study, subwatersheds within the Jacaré-Pepira basin were chosen as landscapes. Landcover classes where considered as the most representative components of the landscapes and a Thematic Mapper (TM) image as the mean for quantifying them. Although remote sensing images are very effective for providing a synoptic view of landscapes using a systematic sampling grid, the shape and the size of each sampling unit (pixel of 30 by 30 meters with TM) are not neutral and impose an artificial view of the objects. However, this raster approach for landscape analysis is not less objective than a vector approach as there is no absolute limits in a landscape.

2.1. Boundaries extraction

A Landsat Thematic Mapper image, acquired on 9 September 1990, was used to detect and classify landcover boundaries. The study area was the Jacaré-Pepira basin (State of Sào Paulo, South-East of Brazil). It is a sixth order river (Strahler 1957) that drains about 2500 km^2 (Maier 1983; Giometti 1993). Landscapes are dominated by croplands and dry meadows which represent about three quarters of the total surface area. Natural landcovers (semideciduous forests, cerrados and wet meadows) have limited extents and are highly fragmented.

A supervised maximum-likelihood classification was run using red (TM3), near infrared (TM4) and shortwave-infrared (TM5) spectral bands, together with the normalized difference vegetation index (NOVI = (TM4 -TM3)/(TM4 + TM3)). Eight landcover types were distinguished (Table 1). Each class could be easily defined by its spectral signature, except reforested and urban landcovers which showed confusions with other classes and whose limits had to be digitized. About 2.1 OJo of the Jacaré-Pepira basin was unclassed or occupied by clouds, shadows or smokes over burned clearings. These pixels were grouped in a single class and excluded from the analysis. Classification accuracy was tested with field data. The overall accuracy obtained was close to 890Jo with landcover accuracies ranging from 830Jo to 940Jo.

Boundaries were defined as the set of pixels of one landcover type in contact, orthogonally or diagonally, with at least one pixel of another class. To isolate these pixels, in each landcover class, a non-linear edge detection filter was used with a moving window of 3 by 3 pixels. Boundary pixels in contact with the excluded class were not considered in the quantitative data analysis.

Table 1. Landcover classes in the Jacaré-Pepira basin used for the classification of the Thematic Mapper image. Special class codes were used for characterizing boundary types.

Landcover type		Code	Characteristic
Water		1	Rivers, lagoons and waterlogged soils
Meadows	Wet meadows	2	Wet soils, mainly riparian seasonally flooded soils with hydrophilous herbs vegetation
	Dry meadows	4	Chiefly man made meadows usually used for cattle rearing
Forests	Natural forests	8	Semideciduous mesophytic forests and savanna forests ('cerradào')
	Reforested areas	16	Planted forest of *Pinus* and *Eucalyptus*
Crops	Perennial crops	32	Mainly sugar cane, coffee and citrus fruit
	Annual crops	64	Bare soils that correspond to annual crops and young sugar cane and citrus crops
Urban		128	Small towns

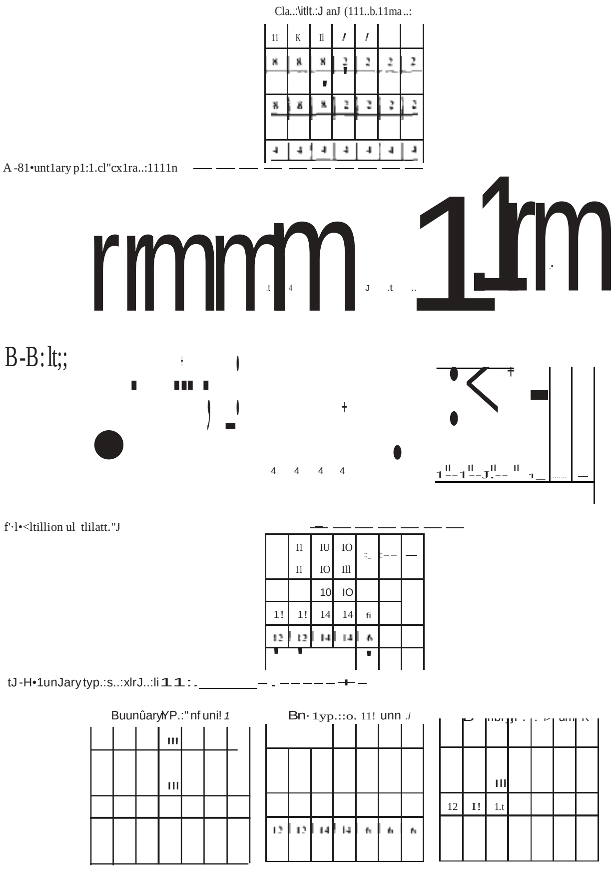


Fig. /. Description of the four main steps of the proposed method for boundary detection and typology definition using three landcovers (codes 2, 4 and 8).

2.2. Typology of boundaries

Once boundary pixels were extracted for each landcover class (Fig. IA), they were further expanded one pixel orthogonally and diagonally (Fig. lB) by using a dilation transform (Serra 1982). Layers of expanded boundaries were overlapped and codes were added (Fig. IC). These new codes for boundary pixels (Fig. ID) could describe any type of contact between the landcover classes since the eight classes were initially coded as 1, 2, 4, 8, 16, 32, 64 and 128 in order to avoid confusions (Table 1). The maximum number of landcover classes that can be analysed with this method depends on the workstation computing capabilities: i.e., 8 classes with 8-bit integer, 16 classes with 16-bit integer, 32 classes with 32-bit integer.

In Fig. 1, three classes were chosen to illustrate the method: wet meadows (code 2), dry meadows (code 4) and natural forests (code 8). A boundary pixel with the code 10 is, without any doubt, a boundary pixel between natural forests (8) and wet meadows (2). A boundary pixel with the code 12 is a contact pixel between dry meadows (4) and natural forests (8). In this example, only one type of convergency point is presented with the code 14 (wet meadows + dry meadows + natural forests).

2.3. Boundary indices

2.3.1. Indices of boundary proportion

From the classified image and from the layers of

Table 2. Indices used to characterize boundary proportion and complexity.

A. Indices of landcover and boundary proportion	
$pi = Ai/A$	Proportion of landcover i where: Ai is the area of landcover i A is the area of landscape
$qi = Bi/B$	Proportion of landcover boundary i where: Bi is the boundary area of landcover i B is the landscape boundary area
$Fi = Bi/Ai$	Shape index or proportion of boundary area in landcover i
$F = B/A$	Landscape fragmentation index or proportion of boundary area within the landscape
B. Indices of landcover boundary complexity	
$Ci = Bci/Ai$	Proportion of convergency points (or coverts) in landcover i where: Bci is the area of coverts in landcover i
NBi	Number of boundary types in landcover i
$HBi = \overset{NBi}{\underset{k=1}{E}} - qki \cdot \log_2 \%$	Boundary diversity index in landcover i where: qki is the boundary area proportion in landcover i of each boundary type k
C. Indices of landscape boundary complexity	
$C = Be/A$	Proportion of convergency points (or coverts) in landscape where: Be is the area of coverts in the landscape
NB	Landscape boundary richness index, *i.e.* the sum of the number of simple contacts (points where two landcovers converge) and coverts (points where three or more landcovers converge)
$HB = \sum_{k=1}^{NB} - q_k \cdot \log_2 q_k$	Landscape boundary diversity index where: qk is the boundary area proportion in the landscape of each boundary type k

boundaries it is easy to compute the landcover area (Ai) and the landcover boundary area (Bi) for a landcover class (i), and the landscape area (A) for the entire landscape. Indices such as the landcover proportion ($pi = AilA$), the boundary proportion ($qi = Bi/A$) and the fragmentation index ($Fi = Bi/Ai$) can then be derived from these basic parameters (Table 2A). Fi varies from 0 to 1 and increases with the number of fragments (Li *et al.* 1993). Landcovers with compacted shapes have Fi values close to 0 while elongated ones have values near or equal to 1, therefore Fi can also be used as a simple shape index. Similary a landscape fragmentation index (F) can be defined by $F = B / A$, with the landscape area $A = EAi$ and the landscape boundary area $B = EBi$. F values increase with elongated and fragmented landscapes and vary from 0 to 1. However, these indices can just characterize landcover boundaries globally without consideration of the type of adjacent classes.

2.3.2. Indices of boundary complexity

Three indices of landcover boundary complexity were proposed in order to take into account the typology of boundaries including the convergency points (Table 2B):

Ci is the proportion of convergency points in landcover i (*i.e.*, points where landcover i converge with two or more landcovers). Ci values range from 0 to 1 increasing with covert areas. The maximum value 1 is obtained when all the pixels of landcover i are boundaries and all the boundary pixels are coverts.

NBi is the number of boundary types in landcover i. It gives an indication of the landcover boundary richness.

HBi is the boundary diversity index in landcover i. This index, based on information theoretic measures, increases as the number and the area evenness of boundary types increase.

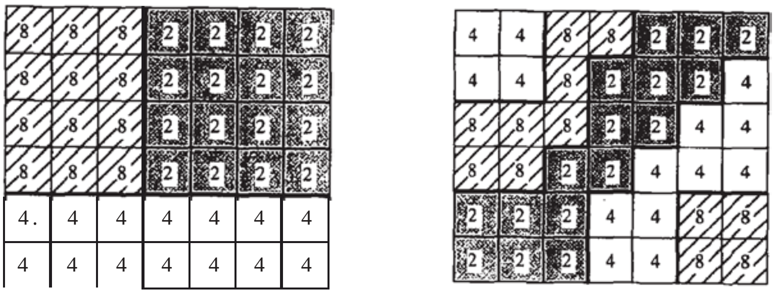
For a given landscape composed by N landcovers, with a surface area A and a boundary area B, the complexity indices are analogous to those for the landcovers (Table 2C):

COMPACT PATIERN

LINEAR PATIERN

Classified image

Classified image



Classified image with boundary types

Classified image with boundary types

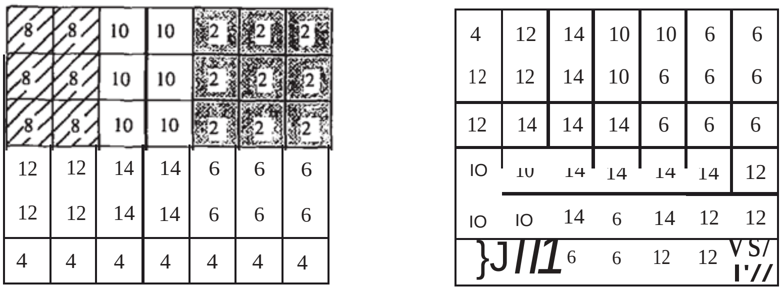


Fig. 2. Examples of boundary characterization for compact and linear patterns with three different landcovers (codes 2, 4 and 8). Both landscapes have the same number of landcover classes (N == 3) and the same proportion of landcover areas ($p_2 = 16/42$, $p_4 = 14/42$ and $p_8 = 12/42$). Boundary indices were computed in Table 3.

Table 3. Landcover and landscape boundary indices values for compact and linear patterns presented in Fig. 2.

	Landcover 2		Landcover 4		Landcover 8		Landscape	
	Compact	Linear	Compact	Linear	Compact	Linear	Compact	Linear
Shape indices	0.44	0.87	0.50	0.93	0.50	0.92	0.48	0.90
Coverts proportions	0.06	0.25	0.14	0.21	0.08	0.33	0.09	0.26
Richness indices	3.00	3.00	3.00	3.00	3.00	3.00	4.00	4.00
Diversity indices	1.45	1.56	1.56	1.55	1.46	1.57	1.97	1.98

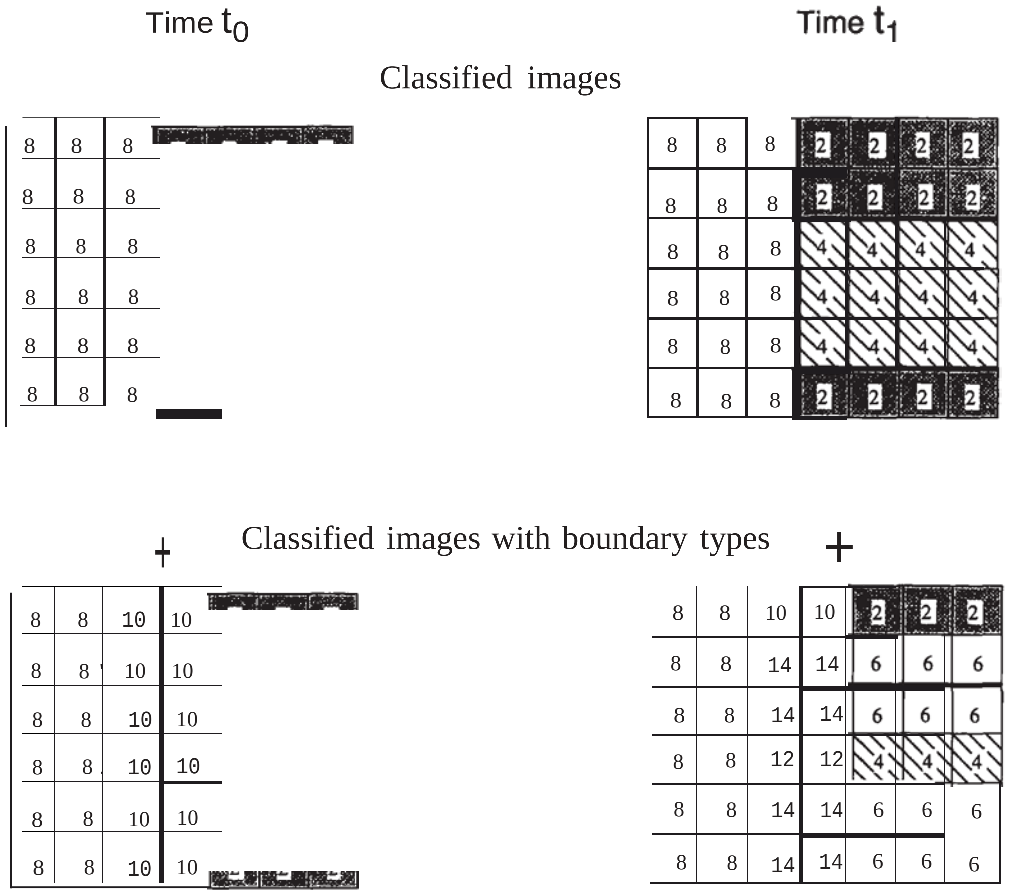
C is the proportion of convergency points in the landscape (*i.e.,* points where three or more landcovers converge). This index varies similarly to Ci.

NB is the number of boundary types in landscape. It gives an indication of boundary richness in the landscape.

HB is the landscape boundary diversity index. This index increases as far as the number of boundaries and their area evenness increase.

2.4. Interpretation of boundary indices

In order to understand how the above indices vary, two contrasted landscapes with the same number of landcovers (N) and the same landcover proportions (pi) were compared (Fig. 2, Table 3). The fragmentation (Fi and F) and the covert (Ci and C) indices were always greater for linear pattern than for compact pattern. Boundary diversity indices (HBi and HB) were generally greater as well. On the other



Boundary indices for landcover 8

Shape index

Fg = 6 / 18 = 0.44	Fg = 6 / 18 = 0.44

Boundary complexity indices

Cg = 0	Cg = 4 / 18 = 0.22
NBg = 1	NBg = 3
HBg = 0	HBg = 1.25

Fig. 3. Sensivity of boundary complexity indices of the landcover 8 due to the fragmentation of landcover 2.

hand, boundary richness indices (Ni and NB) did not help in distinguishing the two types of pattern. According to this example, indices of fragmentation and coverts proportion are particularly sensitive to landscape physiognomy, *i.e.* to the spatial patterns of landcover distribution within a landscape.

Boundary complexity indices provide also new patterns of information compared to previous shape complexity indices, like the fractal dimension (Krummel *et al.* 1987; Turner and Ruscher 1988; Olsen *et al.* 1993) or the spatial contiguity and clustering indices (LaGro 1991) which are calculated for each landcover (or each patch) independently of the other landcovers (or patches). Proposed boundary complexity indices take into ac-

Table 4. Characterization of landcover boundaries in the Jacaré-Pepira basin (means values over the 19 subwatersheds).

Landcover	Area proportion	Boundary area proportion	Shape	Coverts proportion	Boundary richness	Boundary diversity
	$pi = Ai/A$	$qi = Bi/A$	$Fi = Bi/Ai$	$Ci = Bci/Ai$	NBi	HBi
Water	0.01	0.01	0.84	0.32	25.15	3.26
Wet meadows	0.09	0.06	0.77	0.23	27.68	2.83
Dry meadows	0.50	0.16	0.33	0.05	25.74	2.54
Natural forests	0.07	0.04	0.61	0.17	25.05	2.91
Reforested areas	0.09	0.01	0.19	0.03	19.38	2.70
Perennial crops	0.12	0.07	0.67	0.23	25.05	2.93
Annual crops	0.17	0.07	0.45	0.07	23.37	1.96
Urban areas	0.04	0.01	0.32	0.03	7.00	1.24

count the spatial arrangement of neighbouring landcovers. Figure 3 illustrates this distinctive property. Consider indices for the class 8 at time t_0 and t_1. At time t_0, the neighbour class 2 is not fragmented. At time t., the class 2 is fragmented and partly replaced by the new class 4. For landcover 8, the shape (or fragmentation) index (F_8) remains unchanged while its boundary complexity indices are sensitive to landcover change in the neighbour class 2. Therefore, the coverts proportion (Ci), the boundary richness (NBi) and the diversity indice (HBi) for a landcover class i do not only vary according to the spatial pattern of landcover i but also according to adjacent landcovers. The proposed indices are linked to the spatial arrangement of landcovers (*i.e.*, to the complexity of landscape mosaic).

2.5. *Boundary complexity analysis*

Any analysis of boundary complexity may be hampered by the underlying assumptions of the study. First, the *a priori* selection of landcovers has a significant impact on boundary complexity indices. Secondly, the boundary width is maintained constant throughout the landscape while in fact it might vary greatly. Thirdly, the scale of analysis, defined by the grain size and the landscape extend, also has important effects on boundary complexity. Boundary length increases logarithmically with increasing resolution or finer grain size (Burrough 1981, 1986; Warner 1990). The extend of landscape also affects indices, particularly those that are not normalized by the area, as the boundary richness (NBi and NB). Therefore, index values should only be compared in situations where classification procedure, boundary widths and landscape scale are similar.

For this study, proposed indices were calculated within the Jacaré-Pepira basin for 19 fourth order watersheds with an area of about 55 km^2 each, using the same classification (8 landcovers), boundary widths (one pixel) and grain size definition (30 by 30 meters). Pearson correlation coefficients were computed to evaluate the original or duplicate information provided by each boundary index. Special attention was given to the relationships between the boundary proportion indices (qi, Fi and F) and the complexity indices proposed in the present paper (Ci, C, NBi, NB, HBi and HB) in order to bring out the influence of landcover size and shape on boundary complexity, and to understand the relation between landscape fragmentation and its boundary diversities.

3. Results

3.1. *Characterizing boundaries at landcover level*

As mentioned, for the classification of the image over the Jacaré-Pepira basin, eight different landcover classes were selected (Table 1). However, only *5* to 7 distinct classes were observed simultaneously in each of the 19 subwatersheds. Indices were

Table 5. Pearson correlation matrix between landcover proportion indices (pi, qi and Fi) and proposed indices (Ci, NBi and HBi) over the 19 subwatersheds of the Jacaré-Pepira basin (117 classes were analysed).

	Ci	NBi	HBi
pi	-0.513 ***	0.090 ns	-0.254 **
qi	-0.595 ***	0.039 ns	-0.238 *
Fi	0.879 ***	0.005 ns	0.353 ***

ns = not significant; * P < 0.05; ** P < 0.01; *** P < 0.001.

computed by class and by subwatershed. In total, 117 classes were analysed. Ali the landcover boundary indices showed a large range of variation (0.05 :5Fi :50.95; 0.001 :5Ci :50.478; 4 :5NBi :547; O.92 :5HBi :53.69). Mean values of the indices were computed for the eight landcover classes over the basin (Table 4). Results showed that dry meadows were the dominant class in the Jacaré-Pepira subwatersheds, followed by perennial and annual crops. These three classes represented about 80% of the total area. Dry meadows also had the highest boundary proportion in landscape (qi = 0.16), but had a relatively low boundary proportion within the class (Fi = 0.33). The riparian classes (water and wet meadows), composed of elongated patches, presented the highest values of shape index (Fi 0.77), while more anthropic classes (dry meadows, reforested and urban areas), composed of compacted patches, had the lowest shape index values (Fi :50.33). Riparian classes and perennial crops were also characterized by significant proportion of coverts (Ci 0.23) while anthropic classes had lower values (Ci :50.05). Landcover boundary richness index (NBi) had limited range of mean values. Only urban and reforested areas had distinct values. High values of boundary diversity index (HBi 2.83) characterized riparian and natural classes (water, wet meadows and natural forests).

In order to evaluate the relations between area proportion indices (pi, qi and Fi) and proposed indices (Ci, NBi and HBi), a Pearson correlation matrix was computed for Iandcover classes over the 19 subwatersheds (Table 5). Correlation coefficients gave clear indication that while the proportion of a landcover class (p) or the proportion of its boundaries *(q)* increased, boundary complexity tended to decrease with Jess coverts proportion (Ci) and Jess boundary diversity (HBi). The strong correlation of fragmentation (or shape) index (Fi) with two complexity indices (Ci and HBi) showed that the fragmentation of landcover class resulted in a higher complexity of its boundaries. On the other hand, the boundary richness index (NBi) was independent of area proportion indices (pi, qi and Fi).

Table 6. Pearson correlation matrix for boundary landcover indices (117 values over the 19 subwatersheds of the Jacaré-Pepira basin).

	Ci	NBi	HBi
NBi	-0.016 ns		
HBi	0.579 ***	0.419 ***	
N	-0.035 ns	0.648 ***	0.268 **

ns = not significant; * P < 0.05; ** P < 0.01; *** P < 0.001.

The information redundancy between two complexity indices (Ci and HBi) was confirmed by a highly significant correlation coefficient (Table 6). However, the boundary diversity index (HBi) was sensitive to the number of landcover classes (N) and to the number of boundary types (NBi), while the coverts proportion index (Ci) was insensitive to either N and NBi. The richness (NBi) was strongly affected by the number of landcovers (N). When the number of landcovers was low *(i.e.,* N = 5), NBi often reached the maximum value and therefore measured inadequately different degrees of richness.

3.2. Characterizing boundaries al landscape level

Boundary indices were computed for each of the 19 Iandscapes *(i.e.,* subwatersheds) and were ordered by increasing values of the global shape index (F) (Table 7). At landscape level, boundary indices had more limited ranges of values than at the landcover Ievel (0.30:5 F:50.53; 0.05 :5C :50.13; 2.79:5 HB:5 4.27), excepted for boundary richness (26 :5NB :5 104).

The analysis of indices based on a Pearson correlation matrix (Table 8) showed that the relationships at the landscape level were virtually the same

Table 7. Landscape boundary indices for 19 subwatersheds within the Jacaré-Pepira basin.

Subwatershed number	Number of landcovers N	Shape F	Coverts proportion C	Boundary richness NB	Boundary diversity HB
1	7	0.30	0.05	104	4.03
2	6	0.34	0.07	46	3.90
3	5	0.35	0.06	26	3.26
4	7	0.36	0.07	62	3.71
5	7	0.38	0.07	90	3.87
6	5	0.38	0.06	26	3.08
7	7	0.38	0.08	41	3.48
8	7	0.40	0.08	84	4.04
9	5	0.42	0.08	26	3.41
10	5	0.42	0.09	26	3.31
11	7	0.42	0.08	80	4.05
12	6	0.43	0.07	46	3.24
13	6	0.43	0.09	54	3.74
14	7	0.45	0.10	93	3.92
15	7	0.45	0.10	87	3.75
16	6	0.45	0.09	54	2.79
17	6	0.46	0.08	33	3.17
18	6	0.46	0.11	28	3.55
19	6	0.53	0.13	57	4.27

Table 8. Pearson correlation matrix for boundary landscape indices over the 19 subwatersheds of Jacaré-Pepira basin.

	C	NB	HB	N
NB	-0.018 ns			
HB	0.222 ns	0.668 **		
N	-0.009 ns	0.838 ***	0.597 **	
F	0.903 ***	-0.138 ns	-0.041 ns	-0.096 ns

ns = not significant; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

as found at the landcover level. The main difference was that the boundary diversity index (HB) was no more correlated with the fragmentation index (F) and with the coverts proportion (C), contrary to HBi. Landscape boundary diversity index (HB) was still sensitive to the number of landcover classes (N) and to the number of boundary types (NB) in the landscape. On the other hand, the proportion of coverts (C) was still independent of N and NB, and significantly correlated with the fragmentation index (F). The model linking indices C and F explained a large amount of the variance, as stated by a simple linear model (adjusted $R^2 = 0.804$, $p < 0.001$). Landscape boundary richness index (NB) was, like NBi, strongly affected by the number of landcover classes (N) and did not permit a direct comparison of subwatersheds with different landcover richnesses.

4. Discussion

4.1. Spatial informations of boundary complexity indices

Boundary analysis was significantly enriched by the typology proposed in the present paper. The Jacaré-Pepira subwatersheds had only 10 to 18 simple contacts, while the number of convergency points varied from 16 to 86. The proportion of each boundary type k (qki and qk) used to compute boundary diversity indices (HBi and HB) (Table 2) corresponded, in fact, to the probability measurements of contacts between landcover classes used, for example, in landscape patchiness (Romme 1982) or contagion (Li and Reynolds 1993) indices. The quantification of these different boundary types using the boundary richness indices (NBi and

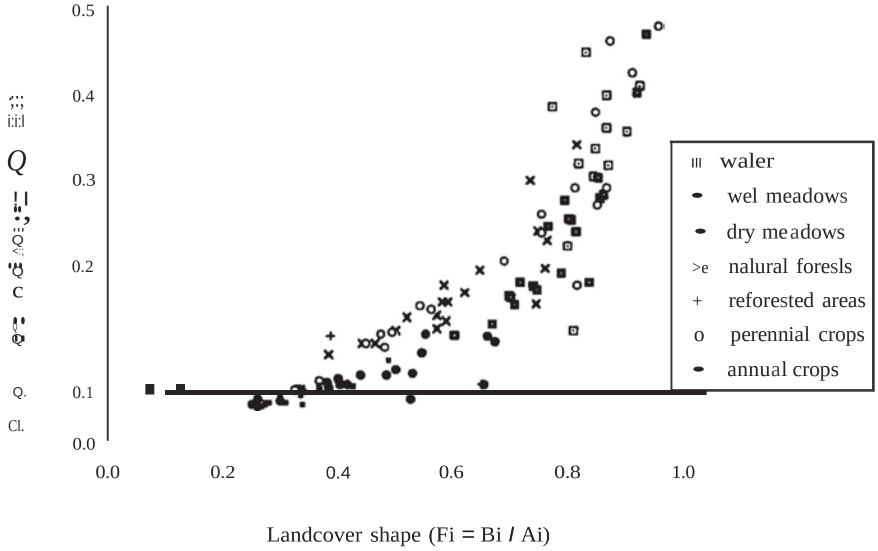


Fig. 4. Relationship between landcover shape (Fi) and the proportion of coverts (Ci) over the 19 subwatersheds of the Jacaré-Pepira basin.

NB), the diversity indices (HBi and HB) and the coverts proportions (Ci and C) provided new information on landscape patterns.

4.1.1. Spatial informations of landcover boundary indices

The values of the diversity boundary index (HBi) provided information on the landscape composition, notably about landcover richness (N), and about landscape physiognomy, expressed by NBi and Ci indices. The proportion of convergency points (Ci) also gave an indication of increasing boundary complexity. But this information was different from the one provided by HBi. Coverts proportion was not correlated with landcover and boundary richnesses (N and NBi, respectively), so Ci provided spatial information on complexity, strongly related with the landcover shape or the fragmentation level (Fi). However, the number of boundary types (NBi) was a poor index for boundary complexity. At the landcover level, the boundary diversity index (HBi) and the proportion of coverts (Ci) appeared to be good indices of boundary complexity.

The analysis of landcover boundary indices revealed also two main trends: firstly, dominant classes, with high values of pi and qi, had low boundary complexity; secondly, elongated and fragmented landcovers (with important values of Fi) had a high boundary complexity (high values of Ci and HBi). The relationships between the shape index (Fi) and the proportion of coverts (Ci) were particularly interesting. An exponential regression analysis between these two factors was highly significant (adjusted $R^2=0.868$, $p<0.001$) (Fig. 4). This relation was expected as Ci can be related to Fi by the equation: $Ci = (Bci/Bi)\ Fi$. However, all classes did not behave similarly. Landcovers with compacted shapes, like reforested areas, were poor in convergency points and the increase of landcover shape (Fi) led only to a little increase in coverts proportion (Ci). On the other hand, landcovers with elongated shapes, like wet meadows and water, were particularly rich in convergency points and an increase in landcover shape (Fi) led to a significant increase in coverts proportion (Ci). Therefore, the slope of the regression of Ci as a function of Fi could be useful in characterizing landcover boundary complexity.

The relations between area proportion indices (pi, qi and Fi) and proposed complexity indices (Ci, NBi and HBi) might be linked to the origin of processes that control the dynamics of landcovers. In Jacaré-Pepira landscapes, landcovers with low boundary complexity were usually artificial classes with large patches (dry meadows, annual and perennial crops), while landcovers with high boundary complexity were natural classes characterized by fragmented patterns with small patches (natural forests) or by elongated patterns, along land-inland water ecotones (wet meadows and water). Krummel *et al.* (1987) found similar results using fractal analysis : patches controlled by natural factors (like topographie or hydrological patterns) had higher fractal dimensions than smaller patches resulting from human factors (like agricultural development). Therefore, both results suggest that the causative mechanisms (or origins) of the patches might be the main factor establishing their shape and boundary complexity.

4.1.2. Spatial informations of landscape boundary indices

At the landscape level, the proposed indices provided informations on the complexity of landscape mosaic. Coverts proportion (C) provided an information on this complexity independently of the number of landcovers (N) and boundary types (NB). On the other hand, the boundary diversity index (HB) allowed an evaluation of landscape composition (expressed by N) and physiognomy (expressed by NB), and can be considered as a spatial index of landscape diversity. Unlike the landcover boundary diversity (HBi), the landscape boundary diversity (HB) was not linked with the shape index (F). This was most probably due to different meanings of Fi and F. At the landscape level, the overall shapes of landcover classes were more diverse than the shapes of a single class. For this reason, the index F should be considered as a simple boundary area measurement or as an indication of the global landscape fragmentation rather than a shape index. Therefore, indices C, HB and F provided complementary perceptions of landscape diversity and fragmentation.

4.2. Ecological issues of boundary complexity indices

The analysis of Jacaré-Pepira subwatersheds showed that landscapes composed by a complicated mosaic had also high proportion of coverts (about *lOOJo* of landscape area, Table 7). Therefore, it is necessary to take coverts into account in analysing pattern and functioning of fragmented landscapes. Several ecological questions need to be understood as well: What is the ecological importance of the different boundary types? Which organisms are favoured by a higher proportion of coverts or boundary diversity? Are coverts ecological traps, like those observed for open-nesting passerines (Gates and Gysel 1978)? Which are the proportion of coverts or boundary diversity level that maximize biodiversity or minimize species extinction at landscape (or metapopulation) scale?

Nevertheless, the ecological interpretation of boundary complexity indices must also be undertaken carefully, as all detected boundaries do not necessarily correspond to ecotones. Two reasons justify this observation. Firstly, a constant width of 30 meters (*i.e.,* the pixel size) was arbitrarily chosen for all the landscape, while obviously the boundary widths would change greatly in accordance with the origins and the processes controlling their development. Secondly, all types of boundaries do not have the same ecological value. Boundaries between human landcovers (*e.g.*, crops, reforested areas, urban areas) are probably less persistent in time and different as habitat than boundaries between natural landcovers or between natural and human landcovers.

The ecological meanings of boundary types and boundary indices will probably be specific to the communities and to the landscapes under study. The contribution of present study was to provide a method to map and quantify boundary complexity that could be used in sampling design and ecological interpretation of field data.

5. Conclusion

The results obtained showed that quantifying boundary complexity was particularly useful for characterizing the spatial pattern (or the landscape physiognomy) and that coverts enriched this quantification. In the case of the Jacaré-Pepira landscapes, elongated and fragmented landcover classes had greater boundary diversity (HBi) and coverts proportion (Ci), while fragmented landscapes had important proportion of convergency points (C) but not necessarily high landscape boundary diversity (HB). These relationships observed for agricultural fragmented landscapes in South-East Brazil should be confirmed by further researches in other landscapes with different spatial patterns.

The proposed approach of boundary characterization can be applied to any type of landcovers and landscapes. Once the conditions of the method are clearly defined, boundary complexity indices are useful for landcover and landscape comparisons. Obviously, initial conditions, like boundary widths or landscape scale should be adjusted according to each ecological process under study. A multiscale approach using different boundary widths, landscape grain and extend definitions could be used if there is not *a priori* scale for the process under study. A local analysis, obtained by using proposed indices in small moving windows (3 x 3, 5 x 5, 7 x 7 pixels . . .), might be more interesting than overall landscape analysis because ecological data, like specific composition, biotic movement or fluxes of nutrient, water and energy, are spatially punctual and more affected by the neighbouring environment. Further researches, using local analysis, should be undertaken to link boundary types and complexity to ecological patterns and processes.

Acknowledgements

This study was supported in part by a research grant of the Brazilian Ministry of Education (CAPES) to Jean Paul Metzger. The authors appreciate the constructive comments made in early drafts of the manuscript by Henri Décamps, Eric Tabacchi, Magali James and anonymous reviewers.

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