RESEARCH PAPER

SCALING THE LANDSCAPE: REVEALING LAND USE AND COVER CHANGE PATTERNS IN THE COLOMBIAN ANDES

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ABSTRACT. Formulating hypotheses about the drivers of land use and cover change (LULCC) involves identifying patterns within the dynamics of the territory. Conventional basin-level analyses often mask localized patterns driven by social issues such as governance and community dynamics. This study examines the variations in LULCC patterns over 35 years (1985–2019) by employing hierarchical intensity analysis of change across different spatial extents of the Grande and Chico River basins in the Colombian Andes. To better capture the influence of governance dynamics, the basin was delineated into two subzones with distinct governance characteristics: Zone A, where community-led conservation efforts and protected areas coexist, and Zone B, characterized by limited community participation and less active governance. Results reveal that the intensity of change accelerated significantly after 2010. During this period, forest and paramo ecosystems in the entire basin showed stationary losses, while pasture and non-vegetated areas exhibited systematic gains. Notably, Zone A demonstrated systematic pasture expansion. In contrast, pasture change in Zone B remained statistically dormant. Transition analysis indicated that cropland was the primary source of pasture gains. Qualitative insights from 3 semi-structured interviews corroborated that governance structures, local institutions, and the growing economic appeal of dairy farming are key drivers of LULCC, particularly in Zone A. These findings emphasize the need to integrate multi-scale quantitative assessments with local governance contexts to inform more effective land-use planning and conservation policy.

KEYWORDS: land use and land cover change, hierarchical analysis of intensity of change, scale, extent

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INTRODUCTION

Studying the land use and cover change (LULCC) processes is important to understand their positive and negative effects on the provision of ecosystem services (Lambin et al. 2003). Such studies start from hypotheses about their causes, where the proximate ones are the direct actions for change, which are often the result of human decisions or mediating agents; and the underlying drivers are the contextual processes that affect those decisions (E. Lambin & Geist, 2008; van Vliet et al., 2016; Verburg et al., 2011). The presence of decision-making agents as moderators between underlying drivers and proximate causes improves the understanding of the role of governance elements such as actors, institutions, and policies (van Vliet et al., 2016). Therefore, it is important to recognize that in many cases, LULCC is a major sustainability problem (Jianchu et al., 2005; Kramer et al., 2017) and as a product of decisions or behaviors of agents embedded in institutional, social, and economic structures that constrain or promote their behavior (Binder et al., 2016; Feola & Binder, 2010; Rindfuss et al., 2004).

Hypothesizing the causes of LULCC involves identifying patterns in the dynamics of the territory. Considering that patterns are not always homogeneous in the common units of analysis (e.g., basins or functional zones), it is important to identify the spatial and temporal differences that may exist to determine an appropriate rate of change (Ruiz Rivera & Galicia, 2016). The scale of observation of phenomena is composed of the dimensions of *resolution and extent*. Carefully choosing these dimensions can favor the detection of patterns (De Koning et al., 1998; Gibson et al., 2000; Kok & Veldkamp, 2001; Sietz et al., 2017; Vincent, 2007). The finest scales (higher resolution or lesser extent) can more readily evidence some LULCC patterns than the broadest ones (Jantz & Goetz, 2007). The studies by (Turner et al., 1989) and (Wu, 2004) assess the effect of the scale on its two dimensions. In fact, most investigations focus on the resolution dimension (Kok & Veldkamp, 2001); however, in this case, we are interested in the extent dimension.

The research questions of this study are: Do different spatial extents of the Grande and Chico rivers basin in the Colombian Andes reveal different patterns of LULCC change, and can these patterns be associated with an underlying driver? To answer this question, we identified and compared LULCC patterns between 1985 and 2019 in the entire basin and in parts of it, which are defined according to governance-related characteristics. Although there are multiple underlying drivers that affect the LULCC processes, governance receives particular interest in this study because it regulates and influences agents' behavior (Berbés-Blázquez et al., 2016; E. F. Lambin et al., 2003; Nunan, 2018; Verburg et al., 2015).

We performed the hierarchical analysis of the intensity of change proposed by Aldwaik & Pontius (2012, 2013) and Robert Gilmore Pontius (2022). Unlike methodologies such as change matrices, this analysis allows us to thoroughly examine the spatial and temporal configurations of LULCC and conclude whether the change is due to systematic processes that need to be studied or to random processes. Although several studies have adopted this methodology (see Farfán Gutiérrez et al. (2016); Ellis et al. (2020); and Feng et al. (2020)), none have contrasted the analyses across different extents of the territories.

The present study offers information about whether the effects of policies and other governance elements on LULCC should be analyzed across the entire basin or in smaller areas within it, given the differences in the dynamics of change across different areas. The paper is structured as follows: Section 2 describes the study zone and the hierarchical analysis of intensity of change; Section 3 presents the results by level of analysis; and Sections 4 and 5 contain the discussion and conclusions of the study.

METHODOLOGY

Study zone and data

This study was conducted in the basin of the Grande and Chico Rivers in the northern region of Antioquia, Colombia. The basin has an area of about 127,986 ha, and its economic structure is based on dairy farming and other agricultural activities, so most of the land is used for these purposes (Corantioquia & Universidad Nacional de Colombia, 2015). It is considered a strategic basin because of the production of dairy products for the whole country (Berrio-Giraldo et al., 2021) and the presence of the Santa Inés paramo and the Río Grande II reservoir. This reservoir supplies water not only to the population settled in the basin but also to the population of Valle de Aburrá (the second most populated center in the country) and meets the national energy demand (Corantioquia, 2020).

We used six land use and cover maps (Fig. 1) from 1985, 1995, 2000, 2010, 2015, and 2019. The categories analyzed were *forest (F)*, *paramo (P)*, *water (W)*, *pasture (PS)*, *crop (C)*, *non-vegetated (NV)*, and unclassified (UC), as described in Table 1. Each map has 1,432,143 pixels, where each pixel has a resolution of 30 m × 30 m and represents one of the seven classes. The maps were provided by Professor Johan Oszwald from the University of Rennes (personal communication, 2020) and were constructed using a supervised classification system with a maximum likelihood algorithm (overall accuracy of 89.67% and a Kappa coefficient of 0.85). It used Landsat images from the TM-5, ETM+7, and OLI-8 sensors available in Google Earth Engine. The images correspond to dates between January 1, 1985, and July 1, 2019.

In recent years, there has been a tendency in the basin to establish environmental management and protection policies in strategic areas, as shown in the left panel of Fig. 2. For example, the environmental authority Corantioquia declared in 2010 and updated in 2020 the Integrated Management District (DMI, as per its acronym in Spanish), which covers the paramo area (Corantioquia, 2010; PNUD & Corantioquia, 2020) and a total extent of 21,603.06 ha. Also, in 2015, the same authority created the Local System of Protected Areas (SILAP as per its acronym in Spanish) in one of its municipalities (Corantioquia & Alcadía de Santa Rosa de Osos, 2015), with a total area of 13,880.42 ha. Both policies delimit preservation, restoration and sustainable use zones.

To assess the effect of different extents (with the same resolution), the analysis of intensity of change of the *entire basin* was also broken down into *Zone A* and *Zone B*, as shown in the right panel of Fig. 2. Although there are several criteria to divide and select the study zones like subbasins or functional zones, in this work we considered governance criteria: villages where the effect of governance is expected to be greater (or lower) due to the area under protection policies and the community attitudes to conservation issues. *Zone A* (see land use and cover map in Fig. A.1 of the annexes) has an approximate area of 24,892 ha (276,583 pixels), and environmental management and protection policies have been implemented in 73.5% of the territory. In addition, the Santa Inés paramo is located in this zone, characterized by having a more active and participatory community in terms of conservation (Marsiglia Rivera, 2017). By contrast, *Zone B* (see land use and cover map in Fig. A.2 of the annexes) has an approximate area of 104,000 ha (1,155,560 pixels), and environmental policies have been implemented in

Table 1. Categories description (Berrio-Giraldo et al., 2024; Corantioquia & Universidad Nacional de Colombia, 2015; Machado et al., 2019)

Category	Description
Forest (F)	Oak forest and stubble. According to the Life Zones Areas, most of the area has very humid low montane forest (bmh-MB) and, to a lesser extent, very humid montane forest (bmh-M).
Paramo (P)	Santa Inés is a paramo where the main water sources that supply several municipalities originate. It is home to important plant formations (195 plant species) with immense genetic and biological value.
Water (W)	Water associated with the Río Grande II reservoir.
Pasture (PS)	Pasture is the basis of the economic structure dedicated to dairy production and dairy agroindustry. Overgrazing is observed in most of the basin.
Crop (C)	Commercial crops such as tree tomatoes and potatoes (commercial scale), and to a lesser extent subsistence agriculture. Potato crops are used to "improve the land" for cattle ranching due to the removal of topsoil to obtain organic matter and the use of high concentrations of fertilizers to adapt the soil.
Non-vegetated	Non-vegetated cover includes infrastructure, housing and mining.
Unclassified (UC)	Unclassified category due to the presence of clouds.

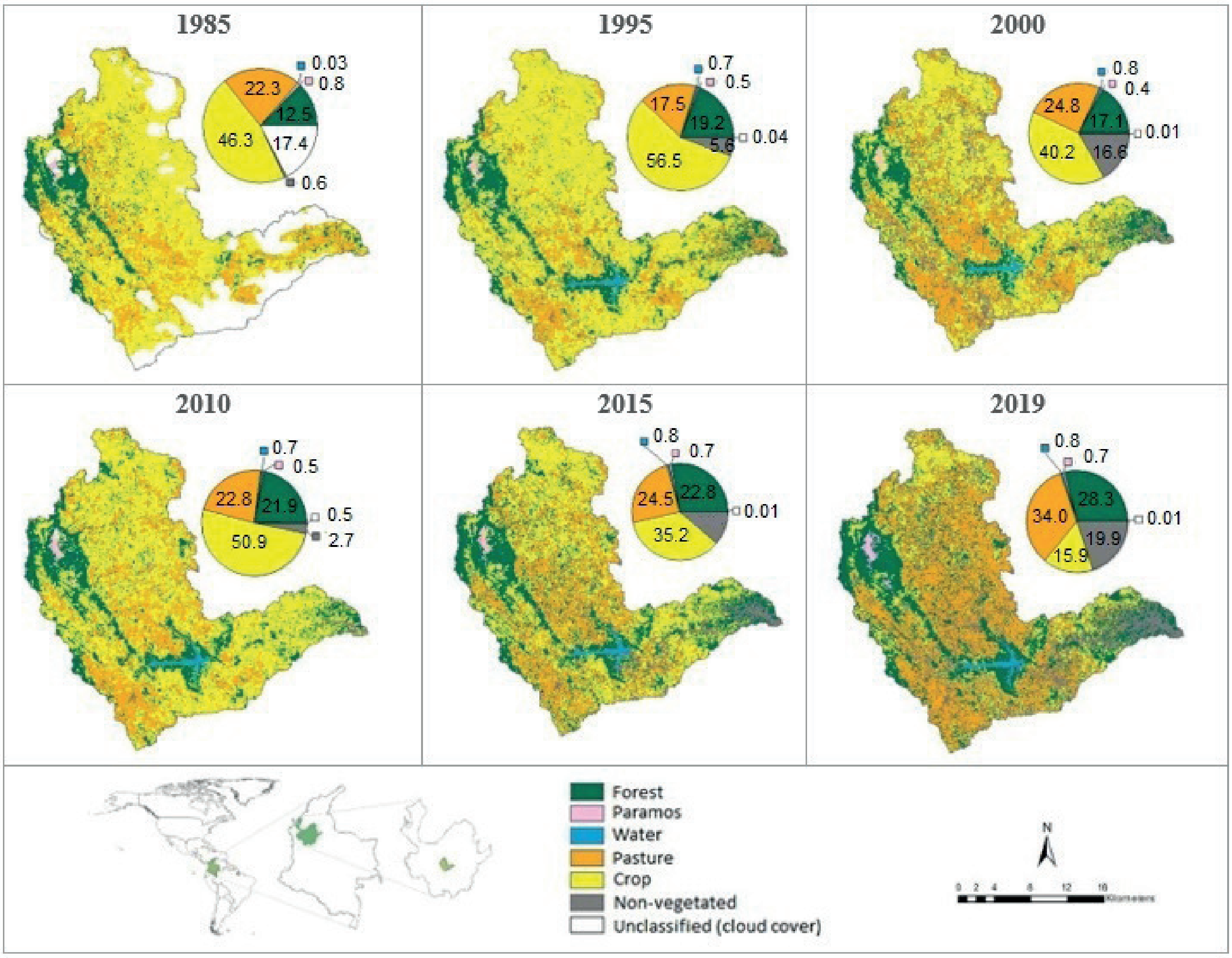

Fig. 1. Land cover maps of the Grande and Chico rivers basin (Antioquia) for six dates

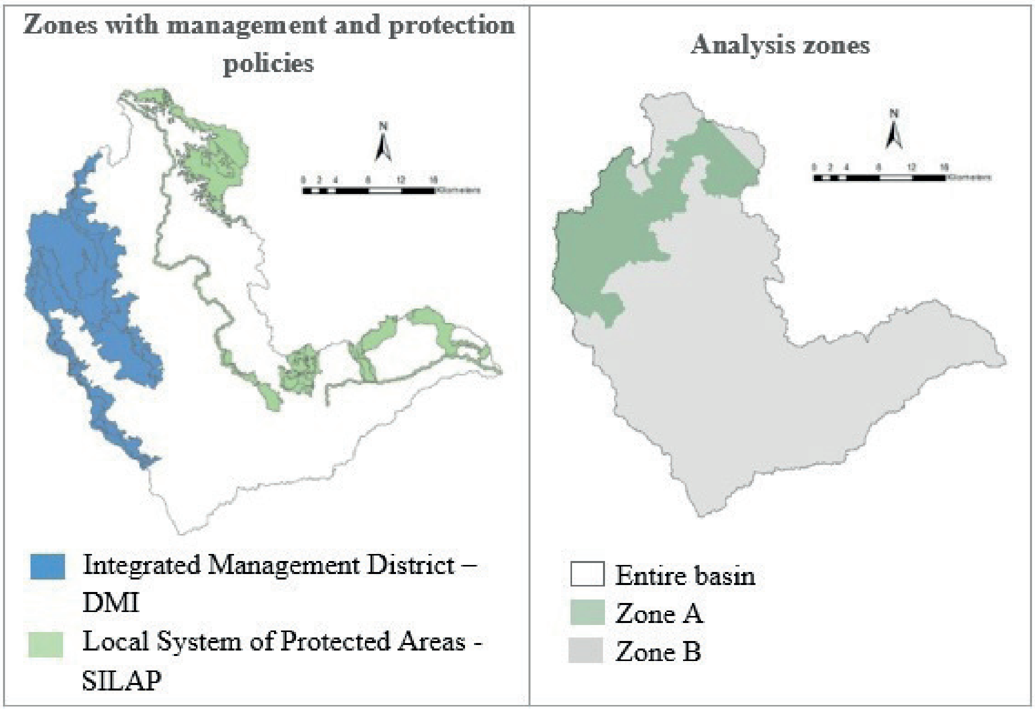

Fig. 2. Zones with management and protection policies in the basin (left) and analysis zones (right)

only 27.5% of the territory. This zone is characterized by having a less active and participatory community in terms of conservation (Berrio-Giraldo et al., 2021).

Given the differences in governance characteristics in both zones, *zone A* is expected to have more area and transitions to the pasture (*PS*) category compared to *zone B*, which is expected to have more area and transitions to *forest (F)*.

Hierarchical analysis of intensity of change

The hierarchical analysis of intensity of change is a methodology proposed by Aldwaik & Pontius (2012, 2013) and Robert Gilmore Pontius (2022). It consists of identifying *stationary patterns*, that is, similar changes across time intervals (Aldwaik & Pontius, 2012), as well as *systematic transitions*, understood as patterns of consequent losses and gains in the use and cover categories (Aldwaik & Pontius, 2013). Thus, it is possible to determine whether the change patterns are the result of systematically intensive processes or are due to random or uniform causes (Pontius et al., 2004). This methodology combines three levels of analysis that gradually increase in detail: interval, category, and transition, which are described in this section. Table 2 shows the notation used in the equations that describe the methodology.

The methodology requires land use and cover maps at different time points, which are employed to create the change matrices. A matrix can be constructed from the changes identified between a pair of maps from different dates, which constitute an interval. The matrices are calculated as shown in Table 3, where the diagonal is the area that remained unchanged for the analyzed time interval. The rest of the cells refer to the area of change, the *Total* Y_{t+1} row shows the area of each category at the second moment (final time point of the interval), and the *Total* Y_t column shows the area of each category at the first moment (initial time point of the interval).

Once we have changed matrices *T-1*, we proceed to analyze change at three levels. At the *interval level*, the most general, we identify how the intensity and size of change vary across the time intervals studied, in terms of Boolean categories: change versus persistence. We compare the annual change for each interval $[Y_t, Y_{t+1}]$, denoted as S_t (Eq. 1), with a uniform rate *U* (Eq. 2) or Uniform Intensity (UI) that would exist if the annual changes were uniformly distributed over the entire time period Y_T-Y_1 (34 years for this study). If $S_t>U$, there is a rapid change; if $S_t<U$, the change is slow.

$$S_t = \frac{area\ of\ change\ for\ interval\left[Y_t, Y_{t+1}\right]}{duration\ of\ interval\left[Y_t, Y_{t+1}\right] * area\ of\ study\ zone} *$$

$$* 100 = \frac{\sum_{j=1}^{J}\left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tij}\right]}{\left(Y_{t+1} - Y_t\right)\sum_{j=1}^{J}\left[\left(\sum_{i=1}^{J} C_{tij}\right)\right]} * 100 \tag{1}$$

$$U = \frac{area\ of\ change\ for\ all\ intervals}{duration\ of\ all\ intervals\ *\ area\ of\ study\ zone} 100 =$$

$$\frac{\sum_{t=1}^{T-1}\left\{\sum_{j=1}^{J}\left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tij}\right]\right\}}{\left(Y_T - Y_t\right) * \sum_{t=1}^{T-1}\left[\left(Y_{t+1} - Y_i\right)\left(\sum_{j=1}^{J}\sum_{i=1}^{J} C_{tij}\right)\right]} 100 \tag{2}$$

Table 2. Notation used in the equations (Aldwaik & Pontius, 2013)

J	Number of categories
i	Index for the category at the initial time point of the interval
j	Index for the category at the final time point of the interval
m	Index for the losing category in the transition of interest
n	Index for the gaining category in the transition of interest
T	Number of time points or maps, equivalent to six in this case
t	Index for the initial time point of interval $[Y_t, Y_{t+1}]$, where *t* ranges from 1 to *T*-1
Y_t	Year at time point *t*
C_{tij}	Number of pixels that transition from category *i* to category j for interval $[Y_t, Y_{t+1}]$
S_t	Annual change for interval $[Y_t, Y_{t+1}]$
U	Uniform annual change over the time extent $[Y_1, Y_6]$
G_{tj}	Annual intensity of gain of category *j* for interval $[Y_t, Y_{t+1}]$ related to the size of category *j* at time point *t*+1
L_{ti}	Annual intensity of loss of category *i* for interval $[Y_t, Y_{t+1}]$ related to the size of category *i* at time point *t*
R_{tin}	Annual intensity of transition from category *i* to category *n* for interval $[Y_t, Y_{t+1}]$ related to the size of category *i* at time point *t*, where $i \neq n$
W_{tn}	Uniform annual intensity of transition from all categories other than *n* to category *n* for interval $[Y_t, Y_{t+1}]$ related to the size of categories other than *n* at time point *t*
Q_{tmj}	Annual intensity of transition from category *j* to category *m* for interval $[Y_t, Y_{t+1}]$ related to the size of category *j* at time point *t*+1, where $j \neq m$
V_{tm}	Uniform annual intensity of transition from all categories other than *m* to category *j* for interval $[Y_t, Y_{t+1}]$ related to the size of all the categories other than *m* at time point *t*+1

Table 3. Change matrix (Aldwaik & Pontius, 2013)

Time point	Time point t+1				
	Category *1*	Category *j*	Category *J*	Total Y_i	Loss *i*
Category *1*	C_{t11}	C_{t1j}	C_{t1J}	$\sum_{j=1}^{J} C_{t1j}$	$\sum_{j=1}^{J} C_{t1j} - C_{t11}$
Category *i*	C_{ti1}	C_{tij}	C_{tiJ}	$\sum_{j=1}^{J} C_{tij}$	$\sum_{j=1}^{J} C_{tij} - C_{tij}$
Category *J*	C_{tJ1}	C_{tJj}	C_{tJJ}	$\sum_{j=1}^{J} C_{tJj}$	$\sum_{j=1}^{J} C_{tJj} - C_{tJJ}$
Total Y_{t+1}	$\sum_{i=1}^{J} C_{tiJ}$	$\sum_{i=1}^{J} C_{tij}$	$\sum_{i=1}^{J} C_{ti1}$	$\sum_{i=1}^{J}\left(\sum_{j=1}^{J} C_{tJj} - C_{tJJ}\right)$	$\sum_{j=1}^{J}\sum_{i=1}^{J} C_{tij}$
Gain of *j*	$\sum_{i=1}^{J} C_{ti1} - C_{t11}$	$\sum_{i=1}^{J} C_{tij} - C_{tjj}$	$\sum_{i=1}^{J} C_{tiJ} - C_{tJJ}$	$\sum_{j=1}^{J}\left(\sum_{i=1}^{J} C_{tiJ} - C_{tjj}\right)$	

At the *category level*, we study how the intensity and size of the net gains and losses of each category vary across time intervals. At this level, the analysis is integrated with the previous level by comparing the metrics of losses L_{ti} (Eq. 3) and gains G_{tj} (Eq. 4) with the UI of losses and gains of all categories S_t (Eq. 1). In other words, the observed intensities are compared with an annual UI of change that would exist if the change within each interval were uniformly distributed across the spatial extent. If L_{ti}, $G_{tj}>S_t$, the category is active; if L_{tj}, $G_{tj}<S_t$ the category is dormant.

$$G_{tj}=\frac{area\ of\ net\ gain\ of\ category\ j\ for\ interval\left[Y_t,Y_{t+1}\right]}{duration\ of\ interval\left[Y_t,Y_{t+1}\right]*area\ of\ category\ j\ at\ Y_{t+1}}$$

$$100=\frac{\left(\sum_{i=1}^{J}C_{tij}\right)-C_{tij}}{\left(Y_T-Y_t\right)*\sum_{i=1}^{J}C_{tij}}100 \quad (3)$$

$$L_{ti}=\frac{area\ of\ net\ loss\ of\ category\ i\ for\ interval\left[Y_t,Y_{t+1}\right]}{duration\ of\ interval\left[Y_t,Y_{t+1}\right]*area\ of\ category\ i\ at\ Y_{t+1}}$$

$$100=\frac{\left(\sum_{j=1}^{J}C_{tij}\right)-C_{tii}}{\left(Y_{t+1}-Y_t\right)*\sum_{j=1}^{J}C_{tij}}100 \quad (4)$$

At the *transition level*, the most detailed, we identify how the intensity and size of the transitions of a category vary across the other categories available for that transition. As for the gain scheme of category *n*, R_{tin} (Eq. 5) accounts for the observed intensity of the annual transition from category *i* to category *n* for interval $[Y_t, Y_{t+1}]$ in relation to the size of category *i* at time point *t*. That is, if a pixel is category *n* at time point *t*, category *n* cannot gain that same pixel at time point *t*+1. W_{tn} (Eq. 6) presents the hypothetical intensity of uniform gain of category *n* over the entire study zone. In the comparison, if $R_{tin}>W_{tn}$, then the gains of *n* target category *i* (category *i* is transitioning towards *n*); but, if $R_{tin}<W_{tn}$, then *j* cannot be changed by *n*.

$$R_{tin}=\frac{area\ of\ transition\ from\ i\ to\ n\ for\ interval\left[Y_t,Y_{t+1}\right]}{duration\ of\ interval\left[Y_t,Y_{t+1}\right]*area\ of\ category\ i\ at\ Y_{t+1}}$$

$$100=\frac{\left(\sum_{j=1}^{J}C_{tij}\right)-C_{tii}}{\left(Y_{t+1}-Y_t\right)*\sum_{j=1}^{J}C_{tij}}100 \quad (5)$$

$$W_{tn}=\frac{area\ of\ net\ gain\ of\ n\ for\ interval\left[Y_t,Y_{t+1}\right]}{duration\ of\ interval\left[Y_t,Y_{t+1}\right]*area\ that\ is\ not\ category\ n\ at\ Y_{t+1}}$$

$$100=\frac{\left(\sum_{i=1}^{J}C_{tin}\right)-C_{tin}}{\left(Y_{t+1}-Y_t\right)*\sum_{j=1}^{J}\left[\left(\sum_{i=1}^{J}C_{tij}\right)-C_{tmj}\right]}100 \quad (6)$$

In the loss scheme of category *m*, Q_{tmj} (Eq. 7) accounts for the observed intensity of the annual transition from category *m* to category *j* for interval $[Y_t, Y_{t+1}]$ in relation to the size of category *j* at time point *t*+1. For its part, V_{tm} (Eq. 8) presents the hypothetical intensity of uniform loss of category *m* over the entire study zone. Following the same logic as in the case of gains, if $Q_{tmj}>V_{tm}$, then losses *m* of target category *j* (category *j* is transitioning towards *m*); but, if $Q_{tmj}<V_{tm}$, then *m* cannot be changed by *j*.

$$Q_{tmj}=\frac{area\ of\ transition\ from\ m\ to\ j\ for\ interval\left[Y_t,Y_{t+1}\right]}{duration\ of\ interval\left[Y_t,Y_{t+1}\right]*area\ of\ category\ j\ at\ Y_{t+1}}$$

$$100=\frac{C_{tmj}}{\left(Y_{t+1}-Y_t\right)*\sum_{j=1}^{J}C_{tij}}100 \quad (7)$$

$$V_{tm}=\frac{area\ of\ net\ gain\ o\ m\ for\ interval\left[Y_t,Y_{t+1}\right]}{duration\ of\ interval\left[Y_t,Y_{t+1}\right]*area\ that\ is\ not\ category\ m\ at\ Y_{t+1}}$$

$$100=\frac{\left(\sum_{j=1}^{J}C_{tmj}\right)-C_{tmm}}{\left(Y_{t+1}-Y_t\right)*\sum_{i=1}^{J}\left[\left(\sum_{j=1}^{J}C_{tij}\right)-C_{tim}\right]}100 \quad (8)$$

At this level of analysis, we try to determine whether the transitions are *systematic*. A transition from category *m* to *n* is systematic in an interval when, simultaneously, the gains of *n* target *m* and the losses of *m* target *n*; that is, when $R_{tmn}>W_{tn}$ and $Q_{tmn}>V_{tm}$.

Therefore, at each of the three levels, the observed intensities (percentages of the map obtained with Eqs. 1–8) are compared with a UI of change that would exist if the change were uniformly distributed over time and space. When the change patterns persist across intervals, there is stationary change (Farfán Gutiérrez et al., 2016).

The results of the hierarchical analysis of intensity of change are validated by the opinions of three actors selected through convenience sampling. For selecting the actors, we considered the following criteria: (1) At least one of them must inhabit and work in the municipality corresponding to the study area; (2) the actor must be related and know the study area for more than 10 years; and (3) the actor must have different experiences and interests (e.g., conservation role or productive role).. In sum, the selected actors were i) an officer of the Municipal Agricultural and Livestock Technical Assistance Unit, ii) an ex-officer of DMI and actual NGO member, and iii) an officer of the environmental authority. Opinions were collected through semi-structured interviews comprising 20 questions, conducted in May and June 2022. The first two actors were interviewed in person, while the last one was interviewed virtually.

RESULTS

This section analyzes the results of the changes in five time intervals, both in the *entire basin* and in *zones A* and *B*, resulting in fifteen change matrices. The matrices take the form shown in Table 4, which corresponds to the *entire basin* during the first interval (1985–1995), where there were changes in 57,952 ha (45% of the total area).

Despite the importance of the information presented in the matrices, it is necessary to classify the types of change found: *net change* is the difference between the total area of each category within the two-time points, *total change* is the sum of the gain area, and the loss area of each category, and *exchange* is the difference between total change and net change, that is, the area of each category can be the same within the two-time points, but with different locations (Manandhar et al., 2010; Pontius et al., 2004). Table 5 details these values, with the crop (C) category reporting the largest area of change.

First level: time interval

At this level, we seek to identify in what time intervals the annual rate of overall change is relatively slow or fast. To this end, we compare the observed intensities (Eq. 1) with an annual UI of change, which would exist if the change within each interval were uniformly distributed across all times (Eq. 2).

Fig. 3 shows the annual intensity on the left and the observed change on the right for the *entire basin* and *zones A* and *B*. We observe that in no time interval and in no analysis zone were there uniform changes because the observed annual rates of change were above or below the reference line (5.46, 4.06, and 5.80, respectively). In addition, no stationary patterns were found because the speed of change across intervals was variable. The annual intensity of change was fast in the second, fourth, and fifth time intervals, which suggests that, since 2010, there has been an acceleration in the change processes for all zones. Note that high values of observed change do not necessarily

Table 4. Matrix of changes in the land use and covers (ha) of the entire basin between 1985 and 1995. The land covers are forest (F), paramo (P), water (W), pasture (PS), crop (C), non-vegetated (NV), and unclassified (U). Diagonal entries show persistence, while off-diagonal entries show transition

Land use-cover 1985	Land use-cover 1995								
	F	P	W	PS	C	I	UC	Total 1985	Loss
F	13417.29	6.66	9.81	150.21	2387.97	183.87	0.99	16156.8	2739.51
P	29.88	364.77	2.25	45.72	510.57	104.58	16.74	1074.51	709.74
W	1.53	-	16.02	0.27	0.09	22.77	-	40.68	24.66
PS	2847.6	0.09	285.48	13001.58	10992.69	1607.22	0.09	28734.75	15733.17
C	5122.08	120.87	511.2	6307.02	43630.56	4012.47	5.4	59709.6	16079.04
NV	19.35	0.27	72.36	59.85	148.77	482.58	0.09	783.27	300.69
U	3243.33	143.46	-	3036.06	15179.4	762.93	28.08	22393.26	22365.18
Total 1995	24681.06	636.12	897.12	22600.71	72850.05	7176.42	51.39	70940.88	
Gain	11263.77	271.35	881.1	9599.13	29219.49	6693.84	23.31		

Table 5. Percentage of total change (TC), net change (NC), and exchange (EXC) between each interval of the six time points for the *entire basin*

	1985-1995			1995-2000			2000-2010			2010-2015			2015-2019		
	TC	NC	EXC	TC	NC	EXC	TC	NC	EXC	TC	NC	EXC	TC	NC	EXC
F	10.86	6.61	4.25	7.38	2.06	5.32	10.23	4.82	5.41	11.85	5.86	5.99	11.69	0.96	10.74
P	0.76	0.34	0.42	0.42	0.09	0.33	0.30	0.11	0.19	0.37	0.16	0.22	0.37	0.05	0.32
W	0.70	0.66	0.04	0.10	0.08	0.02	0.08	0.06	0.02	0.14	0.04	0.09	0.13	0.02	0.11
PS	19.65	4.76	14.89	13.52	7.27	6.25	15.57	1.98	13.59	14.54	1.63	12.91	17.02	9.51	7.51
C	35.14	10.19	24.95	27.87	16.33	11.54	31.69	10.66	21.03	27.61	15.66	11.95	26.18	19.33	6.85
NV	5.43	4.96	0.47	16.40	11.02	5.38	16.65	13.88	2.77	11.02	8.43	2.59	19.21	8.79	10.42
U	17.37	17.33	0.04	0.17	0.10	0.07	0.60	0.33	0.27	0.48	0.46	0.01	0.01	0.00	0.01

imply high intensity because the latter depends on the duration of the time interval (Eq. 1). For example, in the case of the entire basin, a change of 45% of the area in 10 years (Interval 1) is different from a change of 33% of the area in 5 years (Interval 2).

As for the differences among zones, although they have similar behaviors (the same intervals are above the UI line), they differ in their magnitudes. We observe lower activity in *Zone A* than in *Zone B* in terms of intensity of change (left panel) when comparing the UI values (4.06 and 5.80) and realizing that the values of each interval are closer to the UI in the first case, as well as in terms of observed change (right panel) when comparing the percentages. Moreover, the activity in *Zone A* is lower than that in the entire basin, while the activity in *Zone B* is higher.

Second level: changes in categories

At the second level of analysis, we determine whether the pattern of a category is stable across time intervals in terms of intensity of gains (Eq. 4) and losses (Eq. 3). Fig. 4 presents the intensities of each analysis zone in the five intervals. In all cases, we observe that the intensity of the changes is not uniformly distributed across categories because the bars do not end exactly at the UI line of each interval. Moreover, both the behaviors and magnitudes differ across zones.

In general, the category that has remained active (above the UI line) for all intervals and zones is *non-vegetated (NV)*, always in terms of gains. In other words, it is a stationary change in gains. The *water (W)* and *forest (F)* categories have remained dormant both in terms of losses and gains, except in the first interval (1985–1995). In the case of the *water (W)* category, its activity rate (9.82 in the entire basin and *Zone B*) is explained by the creation of the Río Grande II reservoir in 1991. As for the *forest (F)* category, the rate of gains (4.56 in the entire basin and 5.78 in *Zone B*) displays values close to the UI. Therefore, we can say that, since 1995, these two categories have had stationary inactivity in terms of losses and gains.

When comparing the zones, the UI values of *Zone A* are always lower than those of the *entire basin*, while the UI values of *Zone B* are always higher. This variation may be explained by the proportion of the categories, in the sense that *Zone A* has the highest proportion of *forest (F)* of the three zones (Fig. A.1), and this category is one of the least active in the basin. We should also consider that the *forest (F)* activity in *Zone A* is always lower than in *Zone B*, both in terms of losses and gains.

Each table shows the annual percentage of change for each category, including the UI value. If the bars are above the value, the category is active; if they are below, the category is dormant.

We also wanted to find out which categories are active in the time intervals of fast change (2, 4, and 5). In the *entire basin*, we found that, in these three intervals, the *crop (C)* category was active in terms of losses and the *pasture (PS)* category was active in terms of gains. This demonstrates the prevalence of livestock farming as economic activity in the zone (Corantioquia & Universidad Nacional de Colombia, 2015). Furthermore, since the acceleration in the intensity of change in 2010, the *pasture (PS)* category was active in terms of gains in *Zone A* (with intensities of 6.88 and 9.91 in intervals 4 and 5, respectively), while dormant in *Zone B* (with intensities of 6.57 and 9.74 in intervals 4 and 5, respectively), despite having similar values.

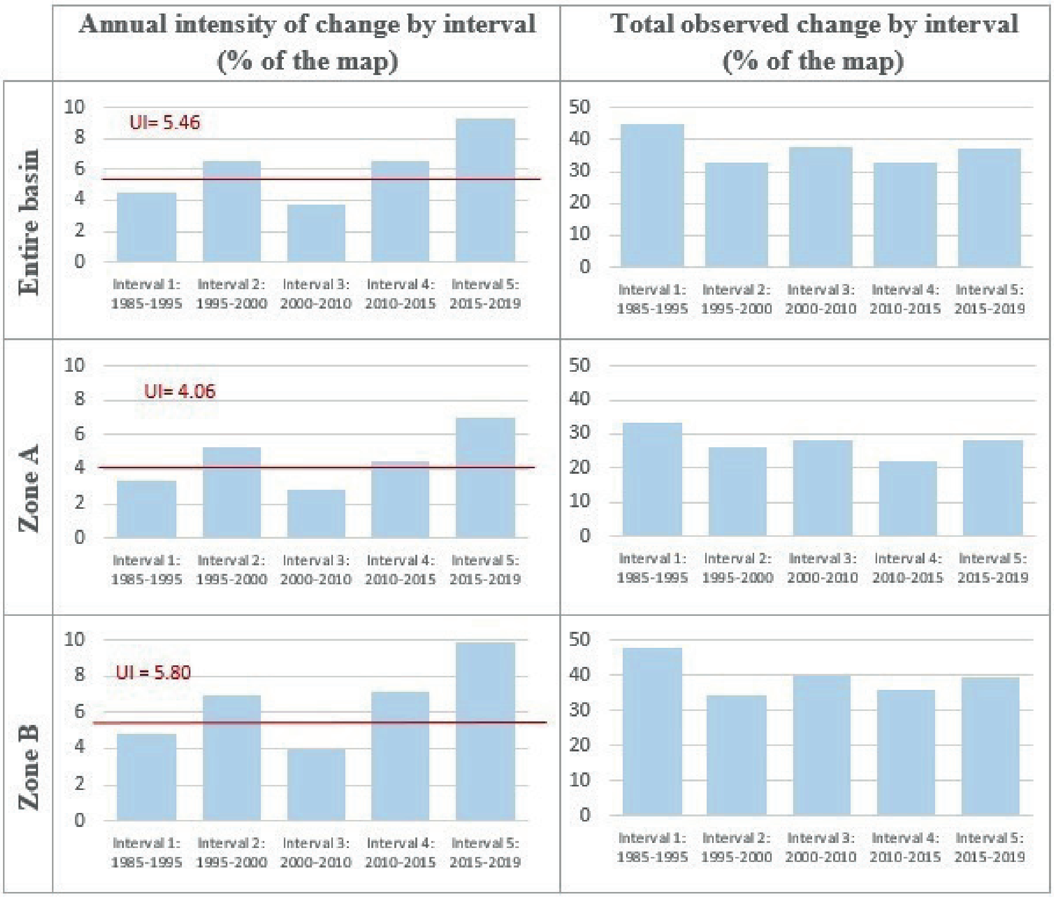

Fig. 3. Analysis of change at the interval level, broken down by zones. On the left, we find the annual intensity of change for each time interval (the red line represents the intensity value if the changes were uniform). If the intensity of change is above the red line, the period has a fast change; if it is below the red line, the period has a slow change. On the right, we find the observed change for each interval

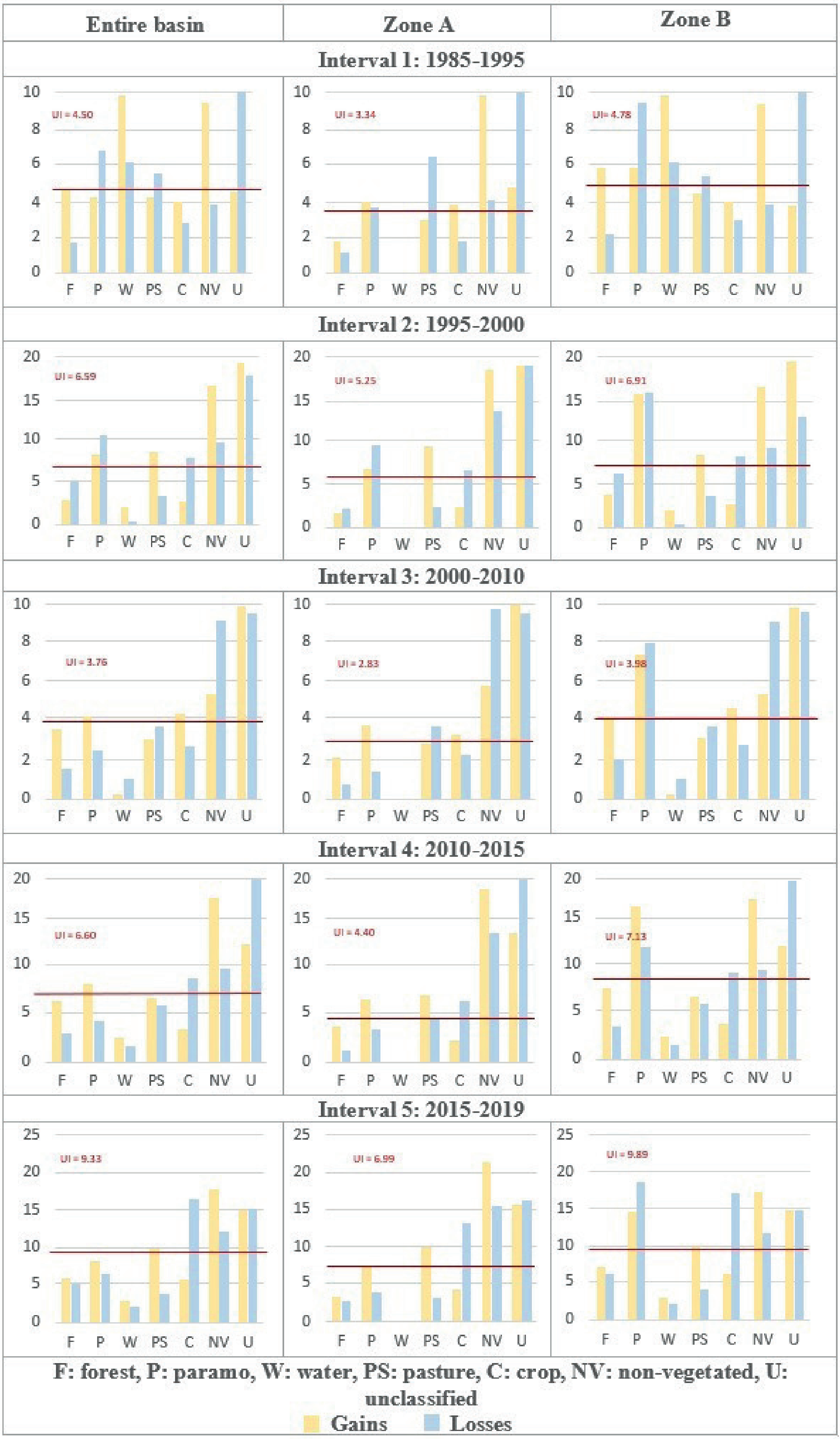

Fig. 4. Analysis of the intensity of change in the categories in the five intervals, broken down by zones

Third level: transitions

Having previously identified the categories that have specific patterns of loss and gain, at the third level of analysis we determine which transitions are particularly intense in a given time interval. In other words, we identify the categories that are targeted (Eq. 5) or *avoided* (Eq. 7), by comparing the observed intensity of each transition with a UI that would exist if the transition were uniformly distributed across the categories available for that change (Eqs. 6 and 8).

For this level of analysis, we present the relevant transition patterns found in the previous levels: i) the stationary change in terms of *non-vegetated (NV)* gains across all intervals and zones, ii) the *pasture (PS)* gain in the fast change intervals in the entire basin and *Zone A*, and iii) the *crop (C)* loss in the fast change intervals across all zones.

Fig. 5 presents the intensity of change from all categories to *non-vegetated (NV)* across all zones. As constant patterns in all intervals and zones, we found that the *crop (C)* category is always susceptible to being replaced by *non-vegetated (NV)* because its intensity of transition is above the UI. Also, we avoid the *forest (F)* category during this transition, as its intensity of transition falls below the UI.

Fig. 6 presents the intensity of transition from all categories to *pasture (PS)* in the two zones that showed active behavior at the category level (*entire basin* and *Zone A*) for the three fast change intervals. We observed that, in the two zones, the *crop (C)* and *non-vegetated (NV)* categories are always targeted to be changed to *pasture (PS)* because their intensity of transition is above the UI. Furthermore, this transition does not involve the other categories.

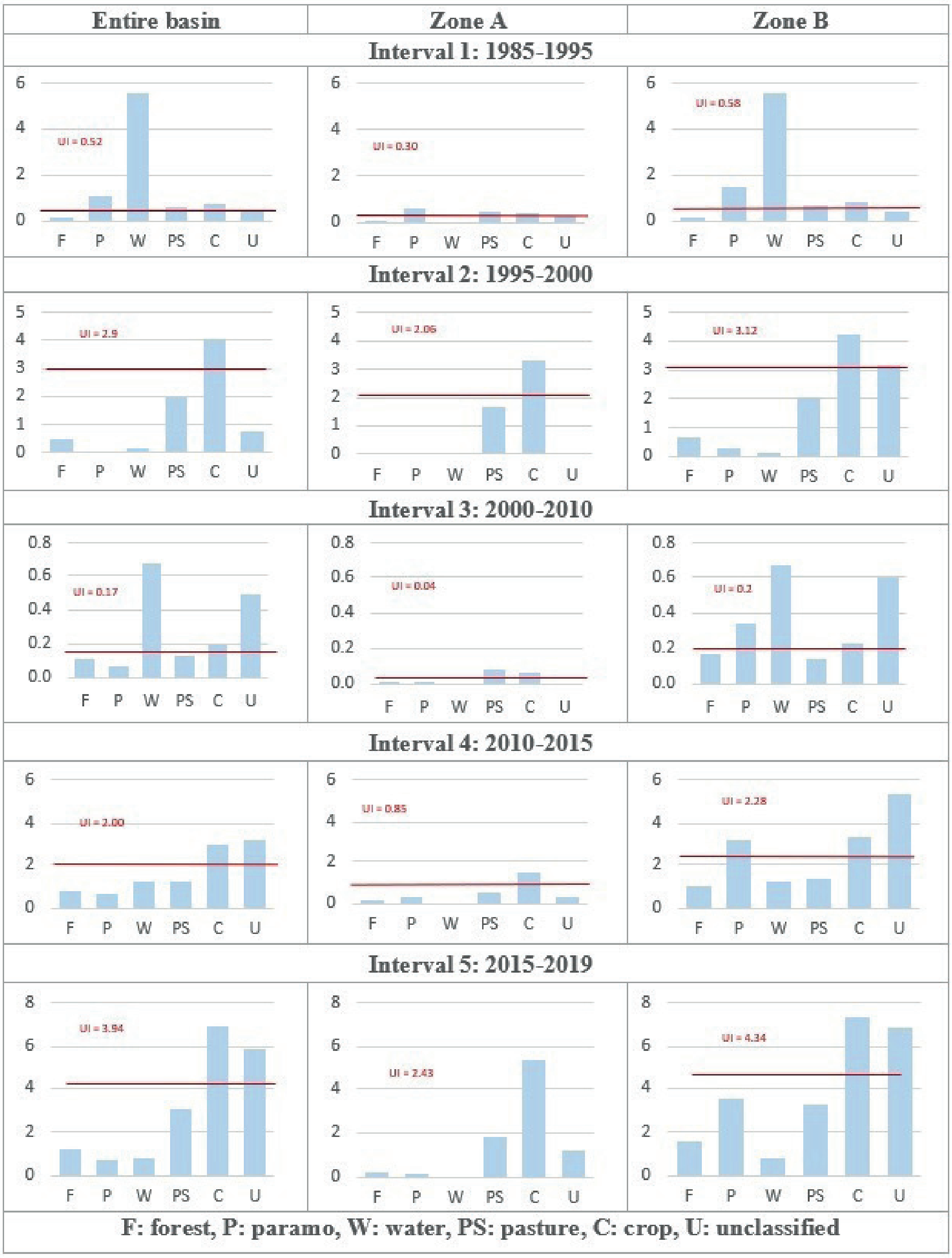

Fig. 5. Analysis of the intensity of the change from all categories to non-vegetated (NV) across all zones and intervals. Percentage of change from each category to non-vegetated (NV), including the UI value. If the bars are above the value, the category is targeted to be changed to non-vegetated (NV); if they are below, the category is avoided from being changed to non-vegetated (NV)

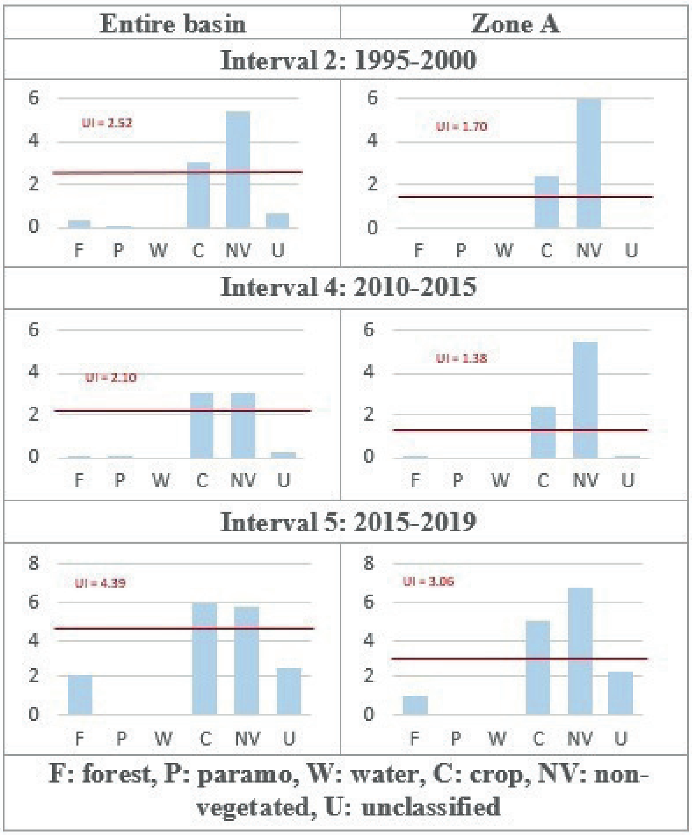

Fig. 6. Analysis of intensity of change from all categories to *pasture (PS)* for the fast intervals in the *entire basin* and *Zone A*. Percentage of change from each category to *pasture (PS)*, including the UI value. If the bars are above the value, it is considered as a target category to be changed to *pasture (PS)*; if they are below, the category is avoided to be changed to *pasture (PS)*

Fig. 7 shows the intensity of transition from *crop (C)* to the other categories for the rapid change intervals and in all zones. Among the stationary transition patterns, we observe that, for the three fast change intervals, there is a transition from *crop (C)* to *non-vegetated (NV)* in all three zones, to *pasture (PS)* in *Zone A*, and to *paramo (P)* in *Zone B* because their intensity of transition is above the UI. In addition, *forest (F)* is the avoided category in this transition across all zones. These results align with the observations in Fig. 5 and Fig. 6, where the target category for the transitions is *crop (C)*.

Analysis of change patterns

Based on the evidence from the three levels, we found an acceleration in the change processes since 2010 for all zones. *Non-vegetated (NV)* gains for all time intervals and *crop (C)* losses since 2010 were also identified as stationary patterns.

Zone A exhibits a lower intensity of change, mainly because it has a greater proportion of *forest (F)* than *Zone B* (Fig. A.1 of the annexes) and the *entire basin*; moreover, this category is the least active. We highlight the *non-vegetated (NV) – pasture (PS) and crop (C) – pasture (PS)* transitions. In fact, the *pasture (PS)* category has had active gains since the acceleration in changes in 2010. Based on these results and the tendencies revealed by (Berrio-Giraldo et al., 2021, 2024), (Corantioquia & Universidad Nacional de Colombia, 2015) and (España, 2020), we hypothesize that the changes in *Zone A* are the result of livestock farming becoming increasingly attractive to landowners, especially over the last decade.

According to the interviews, actor 1 supports this hypothesis for four reasons: (i) "unlike agriculture, dairy farming provides a daily cash flow, which is very important to farmers"; (ii) "the rest of the basin has a rooted dairy culture, which makes the business more feasible"; (iii) "dairy companies have a strong presence in the daily life of farmers; for example, the cooperative Colanta gives them loans, sells to them on credit, trains them, pick their milk… Everything!"; and (iv) "the boom and appreciation of land value: a farm in pasture is worth more than in oak. It has a better price and is more marketable". Similarly, actor 2 states: (i) "livestock farming is cash flow"; (ii) "here *[Zone A]* people already have a livestock farming tradition"; (iii) "there is always someone who buys the milk. Many companies guarantee work," and (iv) "dairy farming has more prestige than agriculture". For their part, actor 3 says that "the companies located in this zone launch important and constant marketing campaigns to captivate dairy farmers." Among other different reasons, actor 1 says that "in this zone *[Zone A]*, due to the types of soil and elevation, conditions are not optimal to produce commercial crops and their marketing is not as good there as it is in the other zone *[Zone B]*." In addition, actor 3 points out that "farmers have acquired a high level of knowledge in the management of pastures."

In contrast, *Zone B* presents a higher intensity of change, mainly because it has a greater proportion of *pasture (PS), crop (C),* and *non-vegetated (NV)* than *Zone A* (Fig. A.2 of the annexes) and the entire basin. We recognize that the factors making livestock farming appealing in *Zone A* may also apply to *Zone B*, given the substantial annual gains in *pasture (PS)*. However, according to the methodology of the hierarchical analysis of the intensity of change, such a change in *Zone B* would be driven by random processes due to the area of the category. To develop hypotheses regarding the causes of change in *Zone B*, we recommend applying the methodology in other extents.

Finally, thanks to the implementation of management and protection policies, along with community

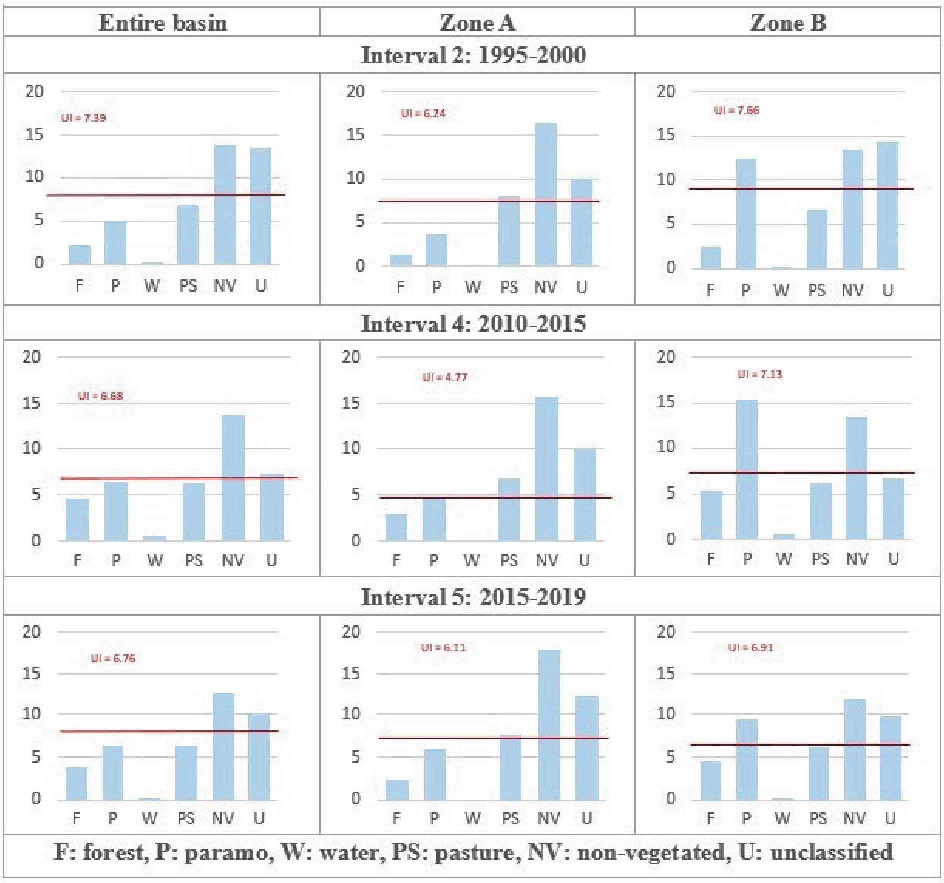

Fig. 7. Analysis of intensity of change from crop (C) to all other categories for the fast change intervals and in all zones. The *percentage* of change to each category from crop (C), including the UI value. If the bars are above the value, it is considered a *target category to be changed from crop (C); if they are below, the category is avoided from being changed from crop (C)*

participation in conservation initiatives in *Zone A*, we would expect a lower intensity of *pasture (PS)* gains than in *Zone B*. It is worth mentioning that this scenario is not an indicator of policy performance because *pasture (PS)* gains do not imply systematic losses in categories such as *forest (F)* and *paramo (P)*. However, provided the evidence of a counter-intuitive change process, we recommend conducting studies in this zone to understand the role of governance and its effect on ecosystem services in the long term.

DISCUSSION

LULCC studies typically use biogeographic criteria, such as basins, sub-basins, or functional zones, to delimit the areas of interest. However, the diverse and heterogeneous causes of LULCC across different regions suggest that alternative delimitations should also be considered. This study proposes using governance conditions as a criterion for delimiting study areas, aiming to reveal previously unknown facts about the drivers and patterns of LULCC.

We found that varying the spatial extent of the study can uncover different types of underlying drivers for the observed changes. By analyzing LULCC across diverse areas, it is possible to isolate multiple causes and gain a deeper understanding of the change patterns. Reducing the spatial extent, in particular, can reveal finer details in LULCC patterns, as supported by the findings of Turner et al. (1989) and Wu (2004).

Once the zone has been selected, other challenges appear. Aldwaik & Pontius, (2012) present the need to understand how large dormant categories can influence the analysis. The comparison between the three zones contributes to this need by showing that larger proportions of dormant categories, such as *forest (F)* in *Zone A*, lower the UI and highlight other active changes.

Regarding the study zone, Berrio-Giraldo et al. (2021, 2024) and España (2020) observed that the villages in *Zone A* have slower LULCC modulated by environmental protection policies, and higher institutional efficiency, as well as by the intrinsic motivation of the community (Marsiglia Rivera, 2017), but they also recognize that *pasture (PS)* has become increasingly important for livestock activities in the entire basin. The dynamics of transitions to *pasture (PS)* that are revealed in this zone are not only local in the basin but also national (Rodríguez Eraso et al., 2013) and regional (see (Guarderas et al., 2022; Wassenaar et al., 2007; Zimmerer & Vaca, 2016)).

Environmental management and protection policies are often designed without community involvement and later communicated, which can lead to conflict (Velásquez Cartagena, 2020). A clear example of this is the transformation of low stubble lands (*forest (F)* in this work) for the expansion of extensive cattle farming (dairy and dual-purpose), a practice driven by the economic interests of local communities, cooperatives, and dairy companies operating in the basin (PNUD & Corantioquia, 2020). Due to noncompliance with existing policies, the DMI was updated in 2020 to address this issue. The revised document emphasizes key strategies such as monitoring restoration on public lands, strengthening control and surveillance, reinforcing the role of forest rangers, and supporting the transition to sustainable agricultural practices. While all these measures are important, the last two play a crucial role in reducing land use conflicts by fostering institutional legitimacy and trust, thereby increasing compliance with regulations (Bodin et al., 2006; Ostrom, 1990) Specifically, forest rangers not only ensure control and surveillance but also act as intermediaries between the community and environmental authorities, helping to align interests.

Additionally, sustained and adequate support for sustainable practices must be tailored to the community's needs to ensure long-term success.

While our research's results are consistent with previous studies in the basin, the country, and the region, the implications and policy recommendations differ due to the more in-depth contextual analysis enabled by the methodology. Specifically, the inactivity or increases of *forest (F)* in the villages of *Zone A* that are observed at the aggregate level (entire basin) could provide positive signals, but the health of ecosystem functions and services cannot be guaranteed until the effect of increased *pasture (PS)* at the disaggregated level (smaller zones) is understood.

To address this complexity, we argue that hierarchical analysis of the intensity of change and other methodologies like nested clustering (see (Sietz et al., 2017)) can be used together to identify LULCC patterns more effectively across scales. Hierarchical analysis serves as an initial step to quantify and visualize the magnitude and distribution of changes across different spatial extents (e.g., basin, sub-basin, villages), providing a broad overview of significant areas of change. Nested clustering can then be applied within these critical zones to group areas based on similarities in LULCC processes or drivers, such as governance conditions or socioeconomic dynamics. This two-step approach ensures that both aggregate trends and localized drivers are captured, linking macro-level patterns with micro-level complexities. By integrating these methodologies, it becomes possible to identify priority areas for intervention while accounting for both overarching trends and finer-scale nuances, essential for informing governance strategies and sustainable land management in heterogeneous regions.

CONCLUSIONS

Many studies analyzing land use and land cover change (LULCC) rely on generic spatial units, such as entire basins. In our study, we have investigated whether different spatial extents within the Grande and Chico Rivers basin in the Colombian Andes reveal distinct LULCC patterns and whether these patterns can be linked to underlying drivers. Our findings highlight the importance of disaggregating analyses and using spatial units defined by specific criteria, such as governance, to identify the scale at which key LULCC processes are most accurately characterized.

More precisely, we found that LULCC patterns vary between the entire basin and its subzones, especially after 2010, a period marked by a significant acceleration in land transformations across all scales. Although the basin as a whole experienced an overall intensification of change, only Zone A – characterized by stronger local governance and community-based conservation efforts- exhibited systematic and sustained gains in pastureland. The evidence suggests that localized socio-economic dynamics, particularly those related to dairy production, are central drivers of LULCC in the region.

Transition-level analysis confirmed that cropland was the primary source of pasture expansion, both in the entire basin and in Zone A. For example, the intensity of crop-pasture transitions during the 2015–2019 interval reached 5.11, notably exceeding the expected uniform intensity of 3.06. These quantitative trends were reinforced by qualitative data from semi-structured interviews, which revealed that dairy farming has become an increasingly attractive livelihood option in Zone A. Interviewees emphasized several motivating factors, including daily cash income, cooperative support, cultural tradition, social prestige, and the increasing value of pastureland.

Overall, this research highlights the importance of integrating scale-sensitive LULCC metrics with contextual analysis of governance and local dynamics. By doing so, it is possible to detect shaded patterns that broader-scale analyses might overlook. These insights are crucial for informing conservation and land-use planning efforts that are responsive to the socio-ecological complexity.

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Appendices

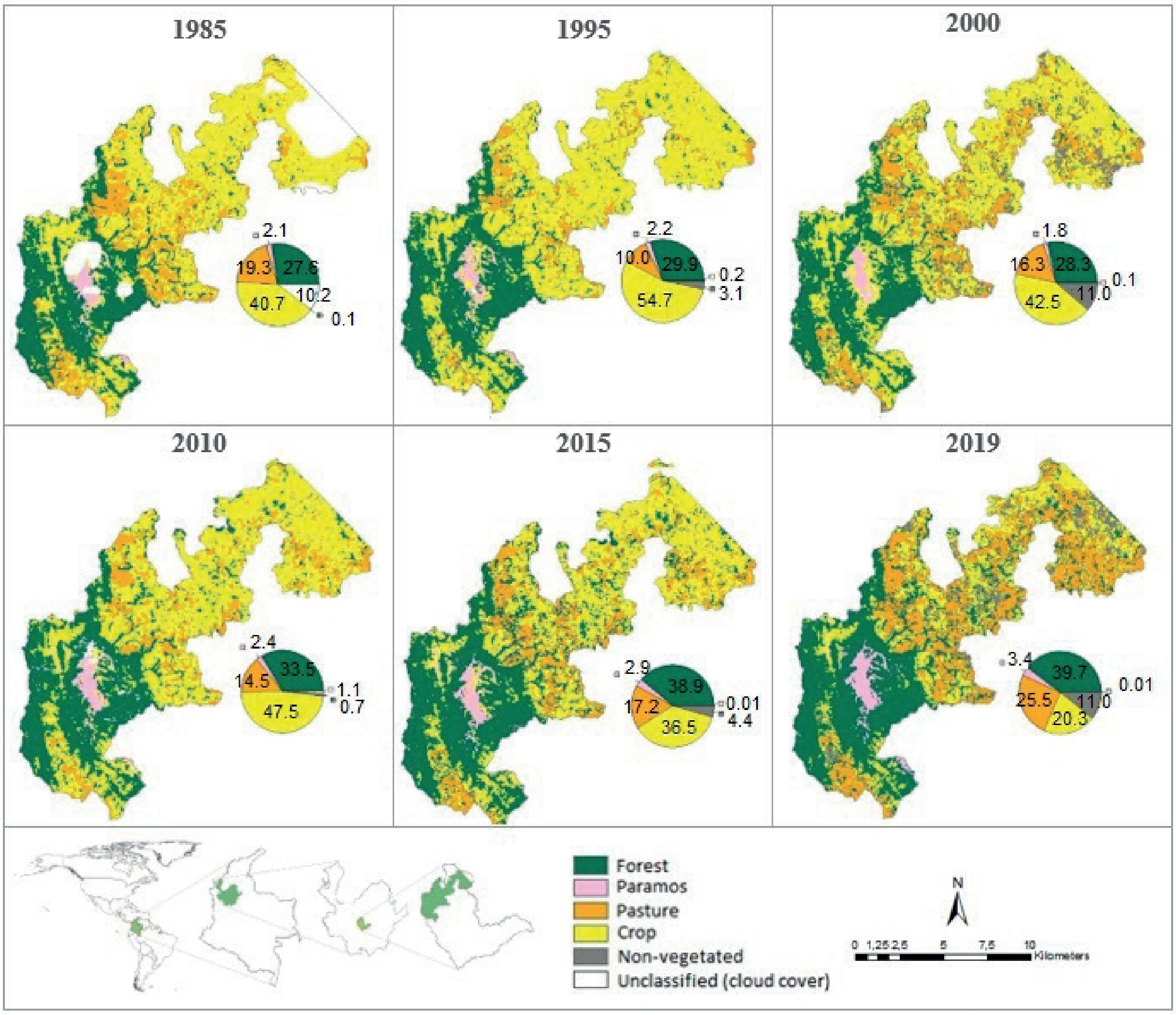

Fig. A.1. Land cover maps of *Zone A* in the Grande River basin (Antioquia) for six dates

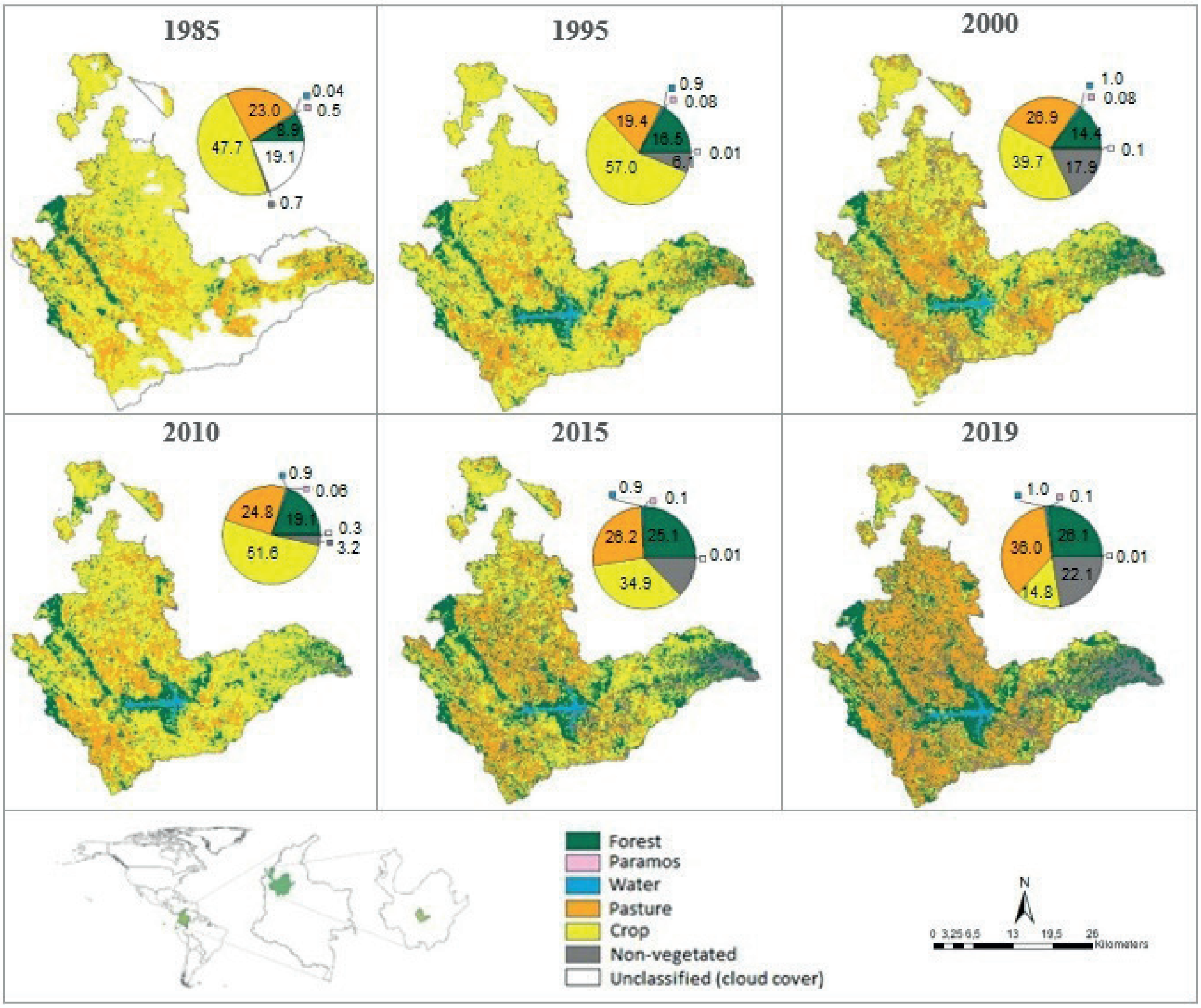

Fig. A.2. Land cover maps of *Zone B* in the Grande River basin (Antioquia) for six dates