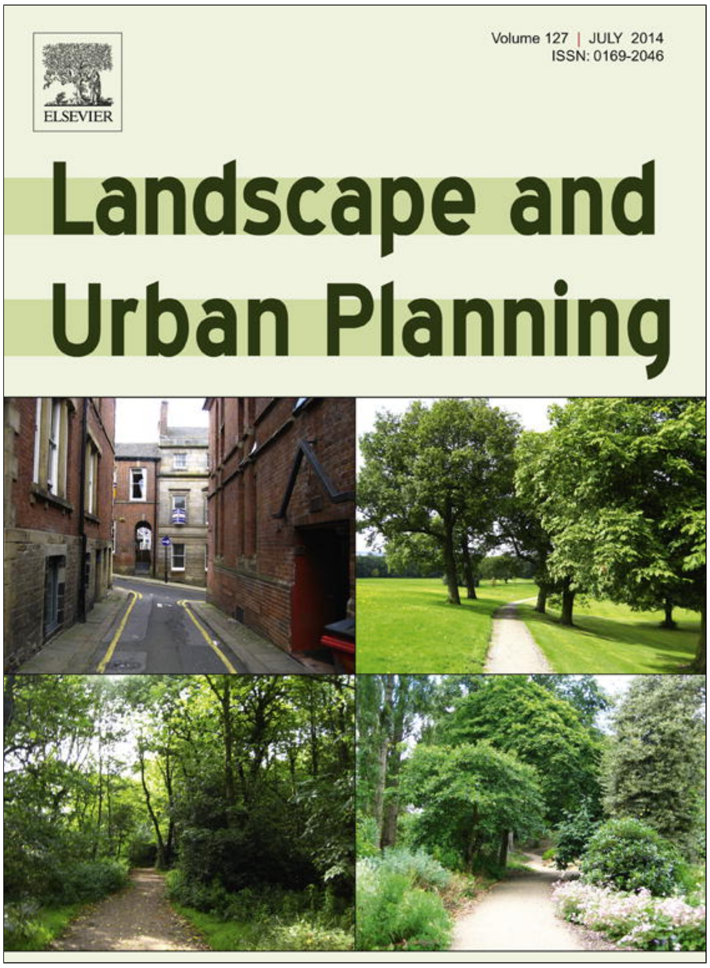
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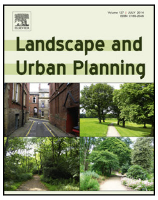

Research Paper

Assessment of swaps and persistence in land cover changes in a subtropical periurban region, NW Argentina

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HIGHLIGHTS

- Between 1972 and 2010, land cover change patterns in a subtropical Argentine region responded to the model of "periurban forest transition" associated with socio-political and economic changes.
- Urban areas expanded in association with population growth, occupying fertile agricultural areas on the foothills.
- Subtropical montane forest expanded over montane grasslands owing to the decrease of marginal agricultural and grazing activities.
- Accompanying growing agriculture demand, agriculture fields became concentrated in flat and fertile areas, resulting in a major redistribution of dry forest.

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ABSTRACT

A detailed spatial analysis of land cover changes was carried out in the periurban area of Great San Miguel de Tucumán and Sierra de San Javier, subtropical Argentina. Post-classification comparison of land cover maps of 1972 and 2010 was used to quantify the level of persistence, net gains, losses and swaps among urban, natural vegetation, and agriculture categories; framed in a hierarchical land use/cover classification. The spatial distribution of land cover changes was related to environmental and socio-economic variables. The overall land cover change pattern of "periurban forest transition" was characterized by urban expansion, agriculture adjustment and associated forest recovery. Montane forests showed a net increase of 10%, expanding over mountain grasslands, which in turn lost 66% of their original area. Dry forests experienced high levels of swaps, being relocated into more humid areas and further away from access roads. Simultaneously, herbaceous agriculture was concentrated in flat areas more suitable for modern mechanized agriculture. In the foothills of the San Javier range, urban areas tripled their original extension replacing fertile agricultural lands (mainly sugar cane). Forest recovery and land-use intensification patterns are usually considered as an opportunity for conservation of biodiversity and ecosystem services. However, these new forests are characterized by the abundance of exotic species with little known ecological properties. Also, the replacement of highly productive agriculture by urban developments, and of natural montane grasslands by forests, imply negative changes in terms of agriculture production, the conservation of grassland biodiversity and landscape configuration with high recreational value.

1. Introduction

Land cover classes and their spatial configuration change constantly owing to natural and anthropogenic causes (Lambin, Geist, & Lepers, 2003). These changes have major implications for ecosystems and societies since different land cover classes have different ecological properties and potential human uses. During the last decades, land use and land cover changes (LUCC) were documented all over the world and they have been recognized as a major component of global environmental change (Dale et al., 2000; Ramankutti et al., 2006; Vitousek, 1994). In Latin America, the best documented trends in LUCC are: (1) *deforestation*, which occurs mainly in tropical and subtropical forests due to population growth, the rising demand for agricultural products, dietary changes and agricultural

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trade (e.g., DeFries et al., 2010; Grau, Aide & Gasparri, 2005; Grau, Gasparri, & Aide, 2008a); (2) *forest recovery or "forest transition"* (Aide & Grau, 2004; Baptista & Rudel, 2006; Grau et al., 2003; Rudel, Bates & Michinguiashi, 2002) which occurs in association with socio-economic changes such as rural out migration and agriculture adjustment (the concentration of agriculture in the most productive lands; Mather & Needle, 1998); and (3) *urban expansion* resulting from intrinsic population growth, rural-urban migration and urban developments with lower population density (Baptista, 2008; Parés-Ramos, Gould, & Aide, 2008). These general patterns are most often analyzed separately, but actually they are part of the same integrated land use dynamics.

Approximately 80% of the South America population lives in cities, and a large proportion of the remaining rural population is located in the nearby periurban areas (United Nations, 2011). Periurban areas comprise the geographically complex units that include cities and the rural landscape located nearby, as well as the functional networks connecting urban and rural activities (Browder, 2002). Despite their comparative small area, urban and periurban landscapes are the ones that more directly affect human population and have a disproportionate effect on ecosystem services with local impact, such as watershed protection or recreational activities (GLP, 2005; Grau, 2010; Rees, 1997). As such, periurban areas are excellent examples of integrated social-ecological systems (Baptista, 2010). Recent studies have shown that several Latin American periurban regions have experienced processes of forest transition (e.g., Aide et al., 2013; Baptista, 2008; Grau et al., 2008b; Parés-Ramos et al., 2008). Periurban forest transitions are characterized by forest recovery within a region which includes a major urban center. In general, understanding periurban forest transitions requires the analysis of the inter-relationship between urban expansion over agricultural fertile lands, the concentration of high-yield agriculture on more suitable areas (e.g., fertile soils and flat lands), and the recovery of forest and other natural vegetation, typically in montane areas due to the reduction of grazing and marginal agriculture. By simultaneously assessing these three processes, this study provides the most detailed analysis of a Latin American periurban forest transition process to date.

Most LUCC studies quantify absolute transitions between land cover classes during a time period (e.g., Baldi & Paruelo, 2008; Shalaby & Tateishi, 2007; Sierra, 2000). However, these analyses are usually insufficient to detect prominent signals of landscape dynamics because they do not take into account exchanges between classes (*swaps*) and their level of persistence (i.e., the area that remained unaltered). Particularly in long-term studies, low values of net change frequently mask high values of swaps, which imply a relocation of land cover categories and, consequently, changes in ecosystem composition or structure between "old" and "new" land cover types. For example, the relocation of forested areas determines the existence of "new forests" (secondary forests) which are disproportionally rich in pioneer or exotic species with potentially different ecological properties from old growth forests (Hobbs et al., 2006; Lugo & Helmer, 2004). Recent regional change analyses have shown that while c. 50 million hectares were deforested in Latin America between 2001 and 2010, during the same period 36 million hectares of forest regrew (Aide et al., 2013), implying that changes in forest distribution affected a larger area than net changes in forest cover. In Central America, Redo, Grau, Aide, & Clark (2012) found that while deforestation dominates in lowland tropical forest, forest regrowth is the dominant trend in montane conifer and dry forests. Such process of forest redistribution involves significant ecological changes which would not be explained by simple analyses of net changes. These results also emphasize that the spatial distribution of land cover changes is not homogeneously distributed throughout the landscape and land cover changes present different spatial patterns conditioned by complex interactions between environmental (e.g., topography) and socio-economic (e.g., population distribution) attributes (Bürgi, Hersperger, & Schneeberger, 2004; Geist & Lambin, 2002; Hietel, Waldhardt, & Otte, 2004). The identification of these "environmental controls" of land cover change, persistence, and redistribution may be useful to predict future changes and to design suitable strategies of land planning.

From a methodological point of view, high levels of reported accuracy in LUCC maps are frequently due to the dominance of static sectors of the landscape (areas of persistence). Few studies have focused on analyzing changes relative to the area of persistence of each class, implicitly assuming that largest classes are also the ones that dominate trends in change (in absolute values). But, small classes can have important ecological effects (Alo & Pontius, 2008; Versace, Ierodiaconou, Stagnitti, & Hamilton, 2008). Another frequently overlooked complexity in LUCC analyses is that land cover classes are to some extent arbitrarily defined, and they reflect a (typically nested) hierarchical structure. Analyzing LUCC at different and disaggregated hierarchical levels allows the identification of important exchanges between land cover categories that go undetected when grouped into high hierarchy categories. For example, Plata-Rocha, Gómez Delgado and Bosque Sendra (2009) analyzed LUCC in metropolitan Madrid, Spain, and found that the values of gains, losses and swaps for each land cover category increase as one moves down the hierarchical level into finer classes. Here, we present a hierarchically organized analysis of change and persistence in the periurban area of the Great San Miguel de Tucumán (GSMT) in subtropical Argentina.

The GSMT is the largest and fastest growing urban agglomeration in subtropical Argentina. It is representative of a typology of cities located in mountain foothills (Grau, 2010), including most cities of northwest Argentina (Salta, Jujuy, Metán, Tartagal) and southeastern Bolivia (Santa Cruz de la Sierra). Therefore, land cover trends in periurban Tucumán can be representative of many areas that harbor a significant proportion of population and agriculture production in subtropical South America.

We carried out a detailed and integrated analysis of LUCC considering the inter-relationships between urbanization, agricultural adjustment and forest recovery. In analyzing LUCC, we have specifically focused on the quantification of swaps (simultaneous gains and losses of a given category in different location) and persistence (area of a given category that remains unchanged) because they can reveal novel land cover processes (e.g., forest redistribution) with important ecological implications. With the same general goal, we analyzed land cover change in a hierarchical scheme of land cover categories, which allowed us to detect patterns of change within high-hierarchy classes (e.g., "agriculture" or "natural vegetation"). More specifically: (1) we quantified LUCC between 1972 and 2010, following a hierarchical scheme of land cover labeling, with special focus on analyzing the level of persistence and swaps between land cover categories, and (2) we related observed LUCC patterns with topographic, climatic and socio-economic variables, in order to explore the environmental controls of the location of both change and persistence.

2. Methods

2.1. Study area

This study was conducted in the periurban area of GSMT, centered at 26°49′ S and 65°13′ W (Fig. 1). GSMT is considered the most important political, economic and cultural urban center in northern Argentina, and the sixth in national order. It includes the capital city of the Tucumán Province and other surrounding municipalities spatially and functionally connected. The population of the GSMT

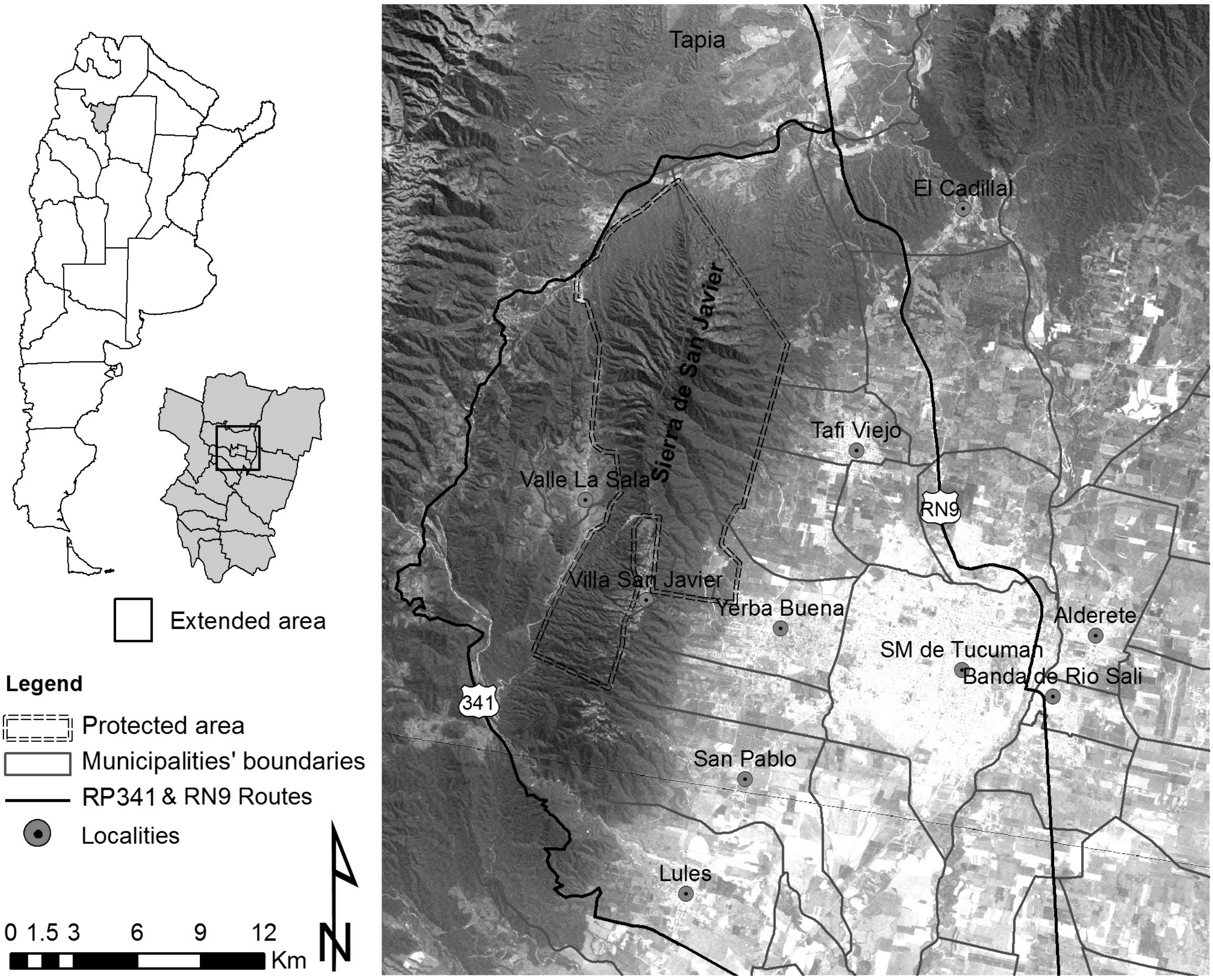

Fig. 1. Image of the study area and its relative location in Tucumán Province, Argentina.

increased from about 400.000 people in 1970 to nearly 1 million in 2010; and its build-up area of expanded considerably in the last decades (Gutiérrez Angonese, 2010).

About 15 km west from the urban area is located the Sierra de San Javier (SSJ), a north to south-oriented mountain range largely covered by subtropical humid montane forest or "*Yungas*", with subtropical monsoonal rainfall regime (>1000 mm/year) concentrated in the summer months (november to march) and strongly controlled by topography (Hunzinger, 1997). San Javier range is an important source of environmental services (hydrological regulations, biodiversity conservation) for GSMT and an important area for tourism and recreational activities (Farías et al., 2010). Nearly 70% of the SSJ is included in a protected area owned by *Universidad Nacional de Tucumán*, (Fig. 1). Native forests in the eastern foothills of SSJ have been historically replaced by agricultural uses, mainly sugar cane, citrus plantations and minor horticultural crops (Brown, Pacheco, Lomáscolo, & Malizia, 2005). Currently, agricultural uses "compete" for the same territory with expanding urban areas. The northern slopes of SSJ are part of the Tapia basin, occupied by dry montane forest areas ("*Chaco Serrano*") with precipitations below 700–800 mm, and accompanied by anthropogenic scrublands and herbaceous agriculture in flatter areas.

The study area extends over 185.000 hectares (Fig. 1). About half of the area is covered by two types of forest: *Yungas* montane forest and *Chaco* dry forest and shrubland. Secondary forests occur near agricultural and urban sectors and are frequently dominated by exotic species, mainly *Ligustrum lucidum, Morus alba, and Gleditzia triacanthos* (Grau, Paolini, Malizia, & Carilla, 2010). The mountain ridge of SSJ and western valleys (La Sala) include herbaceous agriculture as well as natural and anthropogenic grasslands used for cattle grazing.

2.2. Land cover data

Land cover maps were derived from Landsat MSS and TM images taken in 1972 and 2010 (Appendix A), by applying the machine learning algorithm *Random Forest* (Breiman, 2001). Land cover was classified into seven categories organized into a hierarchical scheme (Fig. 2): (1) Subtropical Montane Forest or "*Yungas*" (SMF), (2) Dry Forest or "*Chaco*" (DF), (3) Montane Grasslands (MGr), (4) Anthropogenic Grasslands and shrubland used for livestock and temporary agriculture, a mixed class including also herbaceous agriculture and low-density urban areas (AGr), (5) Sugar Cane (SC), (6) Citrus plantations (CP), mostly lemon, and (7) high-to-medium-density urban and build up areas (Urb). Final accuracy estimation (OOB) showed an overall precision of 81% for 1972 classification and 89% for 2010, identifying citrus plantations, dry forest and anthropogenic grasslands as the categories with lower accuracy (Table 1).

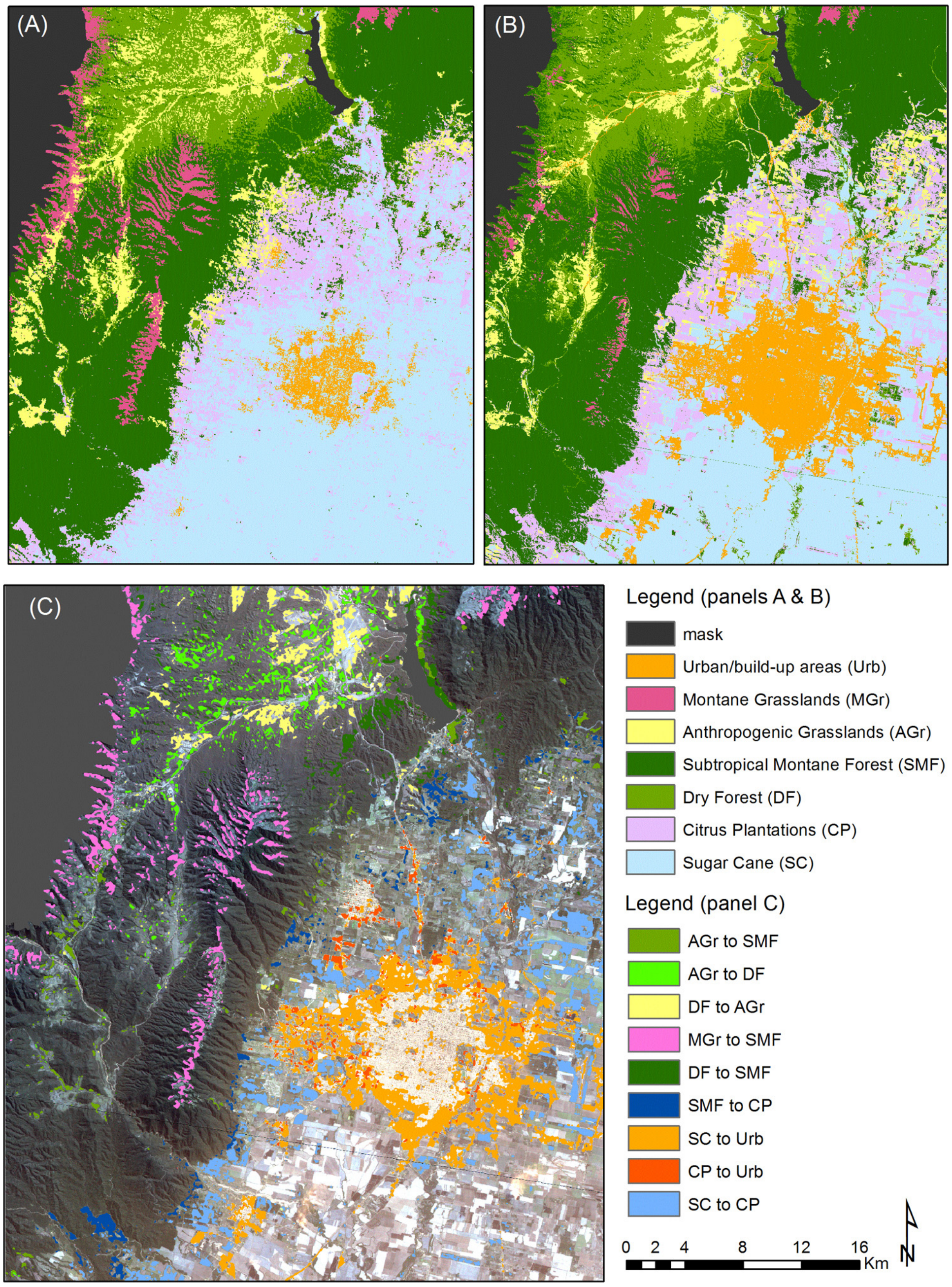

Fig. 2. Land cover maps of (A) 1972 and (B) 2010; (C) Spatial distribution of land cover changes ("from-to" transitions). Abbreviations: SMF (subtropical montane forest), DF (dry forest), MGr (montane grasslands), AGr (anthropogenic grasslands), SC (sugar cane), CP (citrus plantations), Urb (urban/build-up areas).

Table 1
Per-category accuracy evaluation by OOB (Out-of-bag) estimation (Breiman, 2001).

Category	OOB[a]	
	1972	*2010*
Montane Grasslands	9.68	5.41
Anthropogenic Grasslands	***21.21***	10.64
Subtropical Montane Forest	9.09	7.35
Dry Forest	20.00	***19.23***
Citrus Plantations	***52.00***	***20.00***
Sugar Cane	12.77	10.42
Urban/build-up areas	25.00	7.02
Total	18.98	11.11

[a] Values expressed as percentage of error

2.3. *Land covers change analysis*

Patterns of LUCC were summarized in terms of net change, gross gains and losses, and a special focus on persistence and swaps between land cover categories. Swaps refer to simultaneous gains and losses of a given category in different locations (Fig. 3), and are computed as two times the minimum of gains and losses (Pontius, Shusas, & McEachern, 2004). While net change represents the difference in overall quantity, swaps represent changes in location of each category (Alo & Pontius, 2008). To quantify land cover changes we followed the post-classification comparison method of land cover maps from 1972 and 2010. Additionally, since areas that remain unchanged usually dominate the landscape, we expressed changes relative to their persistence by applying the indices proposed by Braimoh (2006): gain-to-persistence (*Gp*),

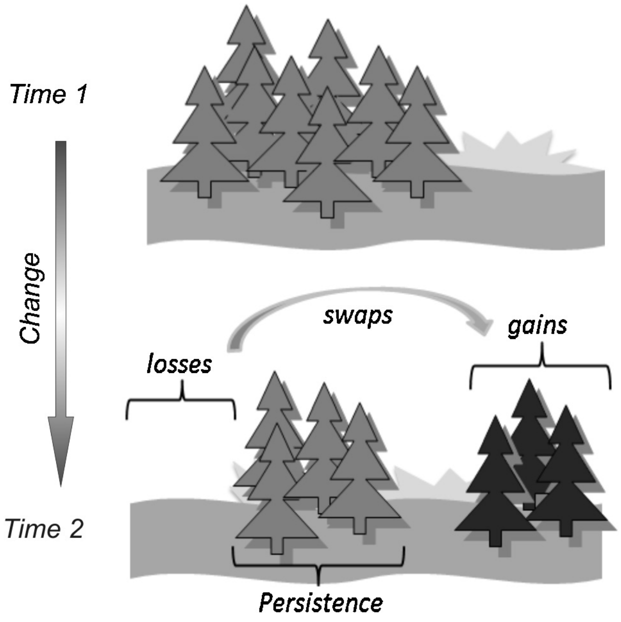

Fig. 3. Schematic illustrations of types of change observed in the landscape. Swaps represent changes in location of a land covers (simultaneous gains and losses) and the persistence represents the area that remains unchanged.

Table 2
Hierarchies of land cover categories for land cover change analysis.

- **1st level categories**
  - 2nd level categories
    - *3rd level categories*
- **Natural or semi-natural areas**
  - Forested areas
    - *Subtropical montane forest*
    - *Dry forest*
  - Montane grasslands
- **Transformed or Human-dominated areas**
  - Agricultural uses
    - *Sugar cane*
    - *Citrus plantations*
    - *Anthropogenic grasslands*
  - Urban/build-up areas

loss-to-persistence (Lp) and net change-to-persistence (Np) ratios; to identify the signals of changes independently from any level of persistence. This approach helps to interpret changes according to the “representativeness” of each category in the landscape.

We analyzed changes at different hierarchical levels to identify transitions between categories that are nested into the same higher level category, thus modifying the estimated gains, losses and swaps. Specifically, we described changes at three levels of analysis, which resulted in a total of the seven land cover classes previously described (SMF, DF, MGr, AGr, CP, SC and Urb, Table 2):

(1st level) includes two broad categories based on land-use: Natural areas (without or with little human intervention, e.g., recreational uses or extensive cattle ranching) and Transformed or human-dominated areas;

(2nd level) mostly referred to land covers with different ecological properties: forest and montane grassland (Natural areas); and agriculture and urban/build-up areas (Transformed areas);

(3rd level) further subdivision of forests into humid and dry forests and agriculture into Sugar Cane, Citrus and Anthropogenic grasslands.

The spatial distribution of land cover changes was analyzed by constructing maps of change, which allowed us to locate areas of gains, losses and persistence for each land cover category, and then relate these areas to a set of environmental and socio-economic variables. To quantitatively examine and test the statistical significance of these relationships (between variables and LUCC) we conducted a discriminant function analysis (DFA; Legendre &

Table 3
Summary of land cover changes between 1972 and 2010.

1st level	2nd level	3rd level	1972	2010	Persistence	Gains	Losses	Total change	Swaps[a]	Net change
Natural or semi-natural areas	Forested areas	Subtropical montane forest	**61,482**	**67,460**	**52,949**	**14,511**	**8532**	**23,043**	**17,065**	**5978**
					86	*24*	*14*		*74*	*10*
		Dry forest	**19,970**	**21,480**	**11,122**	**10,357**	**8848**	**19,205**	**17,696**	**1509**
					56	*52*	*44*		*92*	*8*
		Total forested areas	**81,452**	**88,940**	**71,071**	**17,868**	**10,381**	**28,249**	**20,761**	**7488**
					87	*22*	*13*		*73*	*9*
	Montane grasslands		**7576**	**2482**	**1646**	**835**	**5930**	**6766**	**1671**	**−5095**
					22	*11*	*78*		*25*	*−67*
	Total natural areas		**89,029**	**91,421**	**79,173**	**12,248**	**9855**	**22,103**	**19,710**	**2393**
					89	*14*	*11*		*89*	*3*
Transformed or human-dominated areas	Agricultural uses	Anthropogenic grasslands	**12,518**	**13,109**	**4101**	**9009**	**8418**	**17,426**	**16,835**	**591**
					33	*72*	*67*		*97*	*5*
		Sugar cane	**57,358**	**40,026**	**34,213**	**5812**	**23,145**	**28,957**	**11,625**	**−17,332**
					60	*10*	*40*		*40*	*−30*
		Citrus plantations	**22,254**	**22,731**	**9058**	**13,674**	**13,196**	**26,870**	**26,393**	**477**
					41	*61*	*59*		*98*	*2*
		Total agriculture uses	**92,131**	**75,866**	**66,339**	**9528**	**25,792**	**35,320**	**19,055**	**−16,264**
					72	*10*	*28*		*54*	*−18*
	Urban/build-up areas		**4117**	**17,989**	**4117**	**13,871**	**0**	**13,871**	**0**	**13,871**
					100	*337*	*0*		*0*	*337*
	Total Transformed areas		**96,248**	**93,855**	**84,000**	**9855**	**12,248**	**22,103**	**19,710**	**−2393**
					87	*10*	*13*		*89*	*−2.5*

Values presented in hectares (**bold**) and percentage of area in 1972 (italics).

[a] Percentage of swaps are expressed relative to the total change (% of total change).

Table 4
Indices of change to persistence (according to Braimoh, 2006).

1st Level	2nd Level	3rd Level	Gp	Lp	Np
Natural or semi-natural areas	Forested areas	SMF	0.3	0.2	0.1
		DF	0.9	0.8	0.1
		Total	0.3	0.1	0.1
	Montane grasslands		0.5	3.6	3.1
	Total natural areas		0.2	0.1	0.0
Transformed or human-dominated areas	Agricultural uses	AGr	2.2	2.1	0.1
		SC	0.2	0.7	0.5
		CP	1.5	1.5	0.1
		Total	0.1	0.4	0.2
	Urban/build-up areas		3.4	0.0	3.4
	Total transformed areas		0.1	0.1	0.0

Abbreviations: SMF (subtropical montane forest), DF (dry forest), AGr (anthropogenic grasslands), SC (sugar cane), CP (citrus plantations); Ratios: Gp (gain to persistence), Lp (loss to persistence) and Np (net change to persistence).

Legendre, 1998). The DFA allowed us to detect differences between the location of areas of gains, losses and persistence for each land cover category, based on the following variables: slope, annual precipitation, distance to rivers, and distance to roads; and to identify which variables contribute the most to the distinction among location of areas of change. Such contributions were quantified based on the Wilk's λ parameter (lower values imply a higher contribution of such variable to explain differences between groups) and considered to be statistically significant when $p < \alpha = 0.05$. Also, we obtained the standardized coefficient (b) for each variable in each discriminant function, which represents the contribution of the variable to the discrimination between groups.

3. Results

3.1. Signals of change versus persistence

The first level of analysis compares natural/semi-natural areas against transformed or human-dominated areas. Natural areas (forests + grasslands) experienced a net increase of about 3% of their total area (Table 3). However, the analysis at this first level masks different and opposite-direction changes, as well as varying rates of change within each category; since the largest and most significant changes occurred between low-level categories within the hierarchical framework. Not all natural categories gained area. The net increase of natural areas was largely due to forest regrowth (+9%), which occupied 13% of original agriculture and 75% of original grasslands. In contrast, Montane grasslands decreased considerably (−67%), had the lowest level of persistence (22%), and the loss-to-persistence ratio (*Lp*) showed that losses were equivalent to 3.6 times the area that persisted (Table 4).

The reduction of transformed areas (−2.5%; Table 3) was largely due to the decrease of agricultural lands (−18%), but Urban/build-up areas experienced a more than threefold increase (+337%) of 13,871 ha during the 38-years period, mostly replacing fertile agricultural lands on the eastern foothills of SSJ (Fig. 2c). Net increase (Np) of urban areas was equivalent to 3.4 times the area of persistence (Table 4).

Eighty eight percent of the study area remained unchanged between 1972 and 2010 when analyzed at the higher hierarchical level of analysis. This percentage dropped to77% when considering the second level of analysis, mostly as a result of the transitions from grassland to forest and from agriculture to urban areas; and to 63% at the third level of analysis, reflecting the exchanges between all categories; but particularly within agricultural land covers.

There was an increase in the total area of both forest types. Subtropical Montane Forest (SMF) increased by 10% of its original area (5978 ha) resulting from a net balance of gains nearly doubling the losses (Table 3). However, these changes only involved 14% of the total area of SMF (86% of persistence) and were mostly observed over adjacent Montane Grasslands (MGr) and some areas of Dry Forest (Fig. 2c). Dry Forest (DF) experienced a lower net increase of 1509 ha (8%), but only 56% of the initial area persisted. This means that there were large swaps resulting from simultaneous gains and losses of similar magnitude (Table 3), which implied a relocation of 17,696 ha of DF. While deforestation occurred in the eastern sector, areas of new forests were observed in the western sector of the southern Tapia basin and La Sala valley (Fig. 2c). This relocation pattern reflects a process of "agriculture adjustment", the concentration of agriculture in the most productive lands.

A similar situation in which swaps prevailed over net change was observed in agricultural categories. Anthropogenic Grasslands (AGr) and Citrus Plantation (CP) experienced 5% and 2% of net change, respectively (Table 3). However, these were highly dynamic categories in which less than half of their original area persisted (33% and 41%, respectively) and the highest values of total change were represented by swaps (97% and 98% respectively). The *Gp* and *Lp* ratios of both categories showed that areas of gains and losses were about 50–100% greater than the area of persistence (Table 4). CP gained 13,674 ha (61% of its area in 1972), expanding mainly over Sugar Cane (SC) in the foothills and forests, and "moving" into areas with higher elevation in the foothills of SSJ (Fig. 2c). Also, a similar area of CP was replaced mainly by SC, Urban (Urb) and SMF. AGr gained 9009 hectares, mainly from DF in the eastern sector of Tapia basin, and lost 8418 ha mainly due to the expansion of DF. About 30% of the SC area was lost (17,332 ha) as a result of high levels of transitions to Urban land cover (Fig. 2c), but in this case, the area lost was smaller than the area that persisted (60%).

3.2. Geographic patterns of changes and persistence

Both DF and SMF tended to persist and gain areas in zones with comparatively higher annual precipitation. On average, new SMF pixels had more than 950 mm of annual rainfall and were distributed close to roads, mainly in the southern ridge of the San Javier range where they replaced grasslands (Fig. 2c). Conversely, MGr lost area in humid and close to roads pixels, where they were replaced by urban areas and forests. In the Tapia basin (NW of the study area) we observed a concentration of agricultural uses (AGr) in flatter and drier areas (less than 750 mm y^{-1}), occupying larger and contiguous patches in areas more suitable for modern agricultural activities (replacing DF) due to its capacity for mechanization. DF was relocated, losing area in the northeast (Fig. 2c) and closer to the principal roads (route RN9 and RP341) while gaining area in more humid and less accessible zones (northwestern area and western valleys of SSJ). In the eastern foothills of SSJ, urban expansion occurred mostly over flat areas close to roads, that is, contiguously to already developed areas of GSMT, forcing agricultural uses to move away. CP gained area over humid and steep slopes (in the mountain foothills, mainly to the south), while SC moved to relatively steeper slopes and drier areas, further away from existing urban areas (Fig. 2c).

In general, precipitation and distance to roads were the best predictors of differences in location for all categories as reflected on Wilks's λ values (Table 5). Based on these results, two main patterns can be described (Fig. 4). (1) The "change-stability pattern" is characterized by a spatial segregation of the areas of persistence and the areas of change along an environmental gradient. The distribution of DF along the precipitation gradient illustrates this pattern (Fig. 4b), in which forest areas persist in more humid zones and change (both expansion and deforestation) in drier zones. A similar situation occurs with AGr and SC in a slope gradient, with opposite trends (Fig. 4a). (2) The "displacement pattern" is characterized by a sequential arrangement along the gradient (i.e., loss-persistence-gains), implying a "movement" of a determined land cover category in one direction of the variable. For example, SMF and CP are "moving" into more humid areas, with losses in drier zones and persistence in intermediate zones (Fig. 4b). Similarly, agricultural uses (AGr, CP and SC) are moving far from urbanized areas, losing area close to roads (due to urban growth) and gaining area farther from roads (Fig. 4c).

4. Discussions

From the analysis of LUCC we were able to identify different scale-dependent patterns of change in the periurban area of GSMT-SSJ, which were associated with geographic heterogeneity. At a coarser level of analysis we observed a net increase in natural areas, but lower-hierarchy analysis revealed contrasting trends within categories: while forest expanded (+9%), MGr presented net losses up to 60% and a low persistence (22%; Table 3), which implies the near disappearance of natural areas with important functions in biodiversity conservation and recreational value. Also, heavily transformed areas showed a net decrease, but this pattern combined the retraction of SC with the expansion of urban lands. Indeed, the most significant land cover changes were those observed at the lower hierarchy categories, within natural and anthropogenic classes. The net increase of urban areas (+337%), driven by population growth (+60% in 40 years; Gutiérrez Angonese, 2010) occurred largely over fertile soils previously occupied by sugar cane fields on the eastern foothills (Fig. 2c). Consequently, agricultural activities on foothills were lost or relocated. CP showed high rate of swaps (98%) resulting in a relocation over areas of higher elevation in the foothills of San Javier range.

In the "classical" model of forest transition, agriculture adjustment (the relocation of agriculture lands into more fertile areas; Mather & Needle, 1998) and rural-urban migration driven by regional socio-economic changes (Aide & Grau, 2004) play a key role in promoting forest expansion. While these processes did occur in our study area (e.g., agriculture relocation is clearly visible in the Tapia basin, promoting dry forest redistribution), other specific drivers related to the periurban environment could additionally intervene. For example, the nearby availability of urban jobs may act as a disincentive for rural activities in the SSJ thus favoring the recovery of forests in areas previously used for marginal agriculture or grazing, even if people do not effectively migrate to the city.

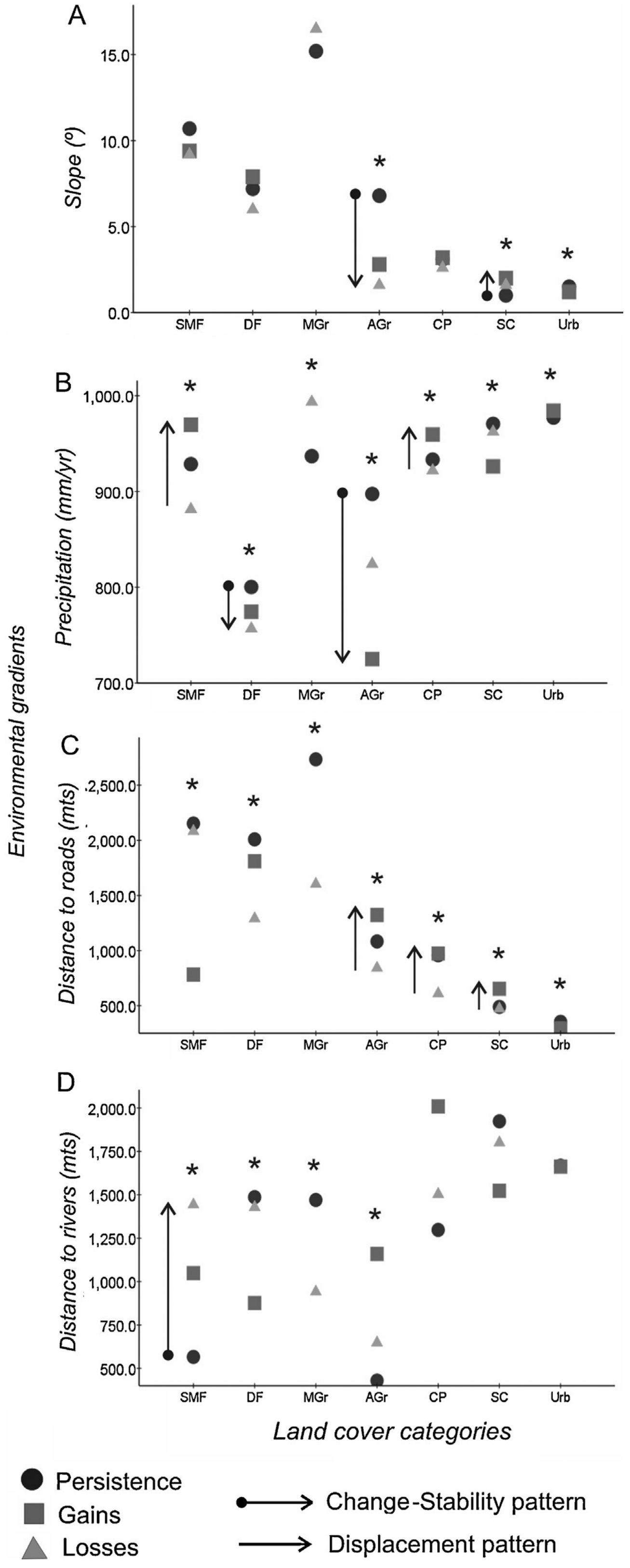

Fig. 4. Graphic representations of spatial patterns of LUCC. (*) Indicates groups with significant differences ($p < \alpha = 0.05$). Abbreviations: SMF (subtropical montane forest), DF (dry forest), MGr (montane grasslands), AGr (anthropogenic grasslands), SC (sugar cane), CP (citrus plantations), Urb (urban/build-up areas). Definitions of "change-stability pattern" and "displacement pattern" in Section 3.2.

Table 5
Relationship between areas of LUCC and explanatory variables.

Category	Change	Slope (degree)	Precipitation (mm)	Distance to roads (meters)	Distance to rivers (meters)
Subtropical Montane Forest ($n = 255$)	Wilk's λ	0.995	0.800[*]	0.731[*]	0.886[*]
	b	0.119	−0.549[a]	0.761[a]	0.038
Dry Forest ($n = 396$)	Wilk's λ	0.987	0.904[*]	0.954[*]	0.941[*]
	b	−0.122	0.882[a]	0.774[a]	−0.368
Montane Grasslands ($n = 146$)	Wilk's λ	0.997	0.946[*]	0.921[*]	0.866[*]
	b	−0.285	−0.194	0.411[a]	0.751[a]
Anthropogenic Grasslands ($n = 252$)	Wilk's λ	0.884[*]	0.340[*]	0.969[*]	0.878[*]
	b	0.131	0.953[a]	0.033	−0.349[a]
Citrus Plantations ($n = 558$)	Wilk's λ	0.995	0.802[*]	0.954[*]	0.964[*]
	b	0.215	0.897[a]	0.256	0.100
Sugar Cane ($n = 195$)	Wilk's λ	0.932[*]	0.609[*]	0.965[*]	0.980
	b	−0.28	0.948[a]	−0.047	0.298
Urban/Build-up areas ($n = 510$)	Wilk's λ	0.992[*]	0.983[*]	0.985[*]	1.000
	b	0.285	−0.568	0.618[a]	0.086

Lower values of Wilk's λ means a higher contribution of such variables to explain differences between groups.

[*] Indicates groups with significant differences ($p < \alpha = 0.05$). The standardized coefficient (b) represents the weighting factor for each variable in the discriminant function (higher value, the better the variable discriminates).

[a] Indicates variables that best correlates with the discriminant function, that is, best characterize difference between groups.

Land "use" activities mostly promoted by urbanites (e.g., recreation, nature conservation) may also translate into a higher valuation of the natural environments in the nearby mountains, so facilitating the increase of forest cover by means of legal, economic or institutional mechanisms (Grau, 2010).

The GSMT-SSJ area is characterized by the presence of two clearly differentiated patterns of LUCC, resulting from different socio-ecological processes: (1) Human use intensification characterizes the lowlands and foothills, where urban areas expanded and are competing with agricultural activities for the most fertile lands. In flatlands, intensification of agricultural activities is due to the increasing demand for agricultural products, leading to the introduction of modern technologies and the concentration of production in areas more suitable for mechanization and the resulting higher yields. (2) Land use disintensification and the abandonment of marginal agricultural activities characterize montane areas, resulting in natural ecosystems recovery, particularly of SMF. As part of this divergent process of intensification-disintensification, DF presented a strong redistribution pattern, with low persistence (<60%) and high percentage of swaps (>90%) in which initial "salt and pepper" pattern composed by mixed areas (shrubland-forest-agriculture) changed to a geographical segregation of land cover types.

Our study supports the inclusion of the effects of urban change (e.g., loss of fertile soils) as well as the consideration of the urban-originated drivers mentioned above, to the forest transition model. This inclusion leads to a definition of the "periurban transition model" which combines trends of urban expansion, agricultural adjustment and forest expansion in periurban regions. In this model, urbanization impacts over natural areas and, in turn, a large proportion of human population is affected by the resulting changes in the environmental services that forests and other natural environments provide (Grau et al., 2008b). Similar processes have been observed in southern Brazil (Baptista, 2008), Dominican Republic (Grau et al., 2008), Ecuador (Rudel, Bates, & Michinguiashi, 2002) and Puerto Rico (Parés-Ramos et al., 2008), where forest regrowth was associated with changes in the urban socio-political and economic context (rural-urban migrations, industrialization and economic globalization). This pattern of LUCC can be particularly relevant in other periurban areas with similar topographic and socio-economic contexts (growing urban centers next to montane areas with steep slopes; Grau, 2010), such as several cities of northwest Argentina (e.g., Córdoba, Catamarca, Salta, Metán, Tartagal) and southeastern Bolivia (Santa Cruz de la Sierra).

Observed LUCC implies changes in the spatial distribution of original land cover types, whether they expand, contract or relocate, that consequently transform the landscape with diverse ecological effects. Forest recovery coupled with agriculture intensification has been considered as an opportunity for the conservation of biodiversity and ecosystem services simultaneously with an increase in agriculture efficiency (Grau & Aide, 2008). Our analysis shows that more complex trends emerge when spatial patterns are analyzed in more detail. The increase of forested areas does represent an opportunity for biodiversity conservation and recreational development, although new forests are often dominated by exotic species (Aide et al., 2000; Lugo & Helmer, 2004), as in the case of the study area (Aragón & Morales, 2003; Grau et al., 2008b). In addition, in this study the expansion of forest also resulted in the reduction and fragmentation of natural grasslands, a process which may be considered as a threat for their biodiversity and recreational value (Farley, 2007; Kiviniemi & Eriksson, 2002). The redistribution of dry forests implies the existence of "new" ecosystems with different ecological characteristics from the original ones (Lugo & Helmer, 2004). The patterns of deforestation in lowlands (mostly represented by dry forests) and reforestation in montane areas (humid forest) is similar to those described by Aide et al. (2013), Grau et al., 2008c and Redo et al. (2012), who concluded that forest redistribution is perhaps more important than net forest change in terms of ecological change. Additionally, urban expansion over the foothills resulted in the loss of highly productive agriculture lands, forcing agricultural activities to migrate to less suitable areas, increasing the cost of production and transport (e.g., Baxendale & Buzai, 2011; López, Aide, & Thomlinson, 2001).

Our methodological approach, which in addition to net changes, takes into account the exchanges between land cover categories, has rarely been applied in LUCC studies, but clearly shows the capacity to quantify the extent of land cover redistribution and the relative importance of "novel ecosystems" in the landscape, with strong implications for ecosystems functioning. Accounting for the level of persistence allows to identify the representativeness of each land cover in the landscape and to focus on the relative magnitude of land cover change as opposed to absolute change; thus identifying significant land cover transitions. Analysis of land cover change into a hierarchical scheme allowed us to describe emergent patterns of change, often obscured by their inclusion into more general categories, but with potentially important ecological effects.

5. Conclusions

Observed LUCC trends in the GSMT-SSJ area could be considered a particular case of land use transitions, a "periurban forest transition", where urban areas interact with the surrounding natural environment, in a way that human activities directly affect the environment and are in turn affected by changes in the ecosystem services they provide. During the past 40 years, the periurban area of GSMT experienced a pattern of rapid urban expansion accompanied by forest expansion associated with agriculture adjustment (forest transition model) and to specific effects derived from the urban proximity (prevalence of urban jobs over rural ones, valuation of recreational and conservation uses by urbanites). High hierarchy trends masked larger changes at lower hierarchical levels, including deforestation in some dry flatlands for agriculture expansion, massive reduction in native montane grassland areas, and significant redistribution of the main crops. This work highlights the importance of detailed spatial analyses of land cover changes, which focuses not only on the net gains and losses experienced by different land covers but also in the exchanges and interactions between them, for example by discriminating between new and old ecosystems, which may have highly relevant ecological implications.

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Appendix A. Satellite data and land cover maps

A.1. Image pre-processing

Land cover data was derived from cloud-free Landsat MSS images taken in September 3, 1972 (path 247 row 79) and Landsat TM images taken in August 28, 2010 (path 231 row 78/79). Images were co-registered using ground control points obtained from ground surveys and were atmospherically corrected to minimize the difference in reflectance within land cover categories through time. Top of the atmosphere radiance units were calculated using the radiometric calibration coefficients for Landsat images updated by Chander, Markham and Helder (2009). Atmospheric corrections were conducted using the modified Dark-Object Subtraction method (Song, Woodcock, Seto, Lenney, & Macomber, 2001). Topographic variables were derived from a SRTM digital elevation model (DEM) to perform digital classification (USGS, 2004). To make all images comparable with the spatial resolution of TM images (30 m), MSS images were resampled using the nearest neighbor method and the DEM was resampled by bilinear interpolation (Toutin, 2004).

A.2. Image classification and validation

Land cover maps were constructed by applying the machine learning algorithm *Random Forest* (RF), based on an ensemble of classification trees (Breiman, 2001). RF builds thousands of tree classifiers using a random sample of the original training data and selecting a random subset of the input predictive variables to determine each split, then their results are combined through a plurality voting process (Breiman, 2001; Gislason, Benediksson, & Sveinsson, 2006). In addition to multi-spectral Landsat data we used ancillary data to improve the classifications and remove confusion between similar land covers, including: (i) vegetation indices (NDVI, SAVI, EVI), (ii) *Tasseled Cap* transformation, (iii) topographic variables (altitude, slope) and (iv) texture images calculated from the spectral bands by a co-occurrence measure (contrast and correlation) (Baraldi & Panniggiani, 1995). For example, confusion between Montane grasslands and Anthropogenic grasslands (with similar spectral behavior) was solved using the variable "altitude", since montane grasslands are located on the mountain top (over 1100 masl) and anthropogenic grasslands are distributed on valleys and lowlands, typically below 800 masl. A selection of the most "important" variables was carried out according to the ranking of importance provided by RF, selecting the combination of predictors that yielded the lowest error (Gislason, Benediksson, & Sveinsson, 2006; Liaw & Wiener, 2002).

We used Random Forest package (Liaw & Wiener, 2011) in the R statistical software (R Development Core Team, 2007) to classify Landsat MSS and TM images. Training of each land-cover map was carried out independently. For the classification tree model runs, 260 invariant training pixels for MSS and 315 for TM were chosen by visual interpretation of satellite data, including seven land use categories of interest:

1. Subtropical montane forest (SMF),
2. Dry forest (DF),
3. Montane grasslands (MGr),
4. Anthropogenic grasslands and shrubland used for livestock and temporary agriculture, a mixed class including also herbaceous agriculture and low-density urban areas (AGr),
5. Sugar cane (SC),
6. Citrus plantations (CP), mostly lemon,
7. high/medium-density urban and build up areas (Urb).

Water bodies (e.g., El Cadillal) and altitudes higher than 1200 m (north-western sector) were excluded from the analysis of LCC (masked).

The final classifications were made running the RF algorithm using the training pixels and the selected predictive variables (total of 11 variables for MSS and 16 for TM), building 1000 classification trees and selecting the default value of random variables at each node. Due to the lack of available field data for 1972 satellite images, accuracy of the final classifications was evaluated using the "out-of-bag" (OOB) estimate of error provided by RF (Liaw & Wiener, 2002).

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