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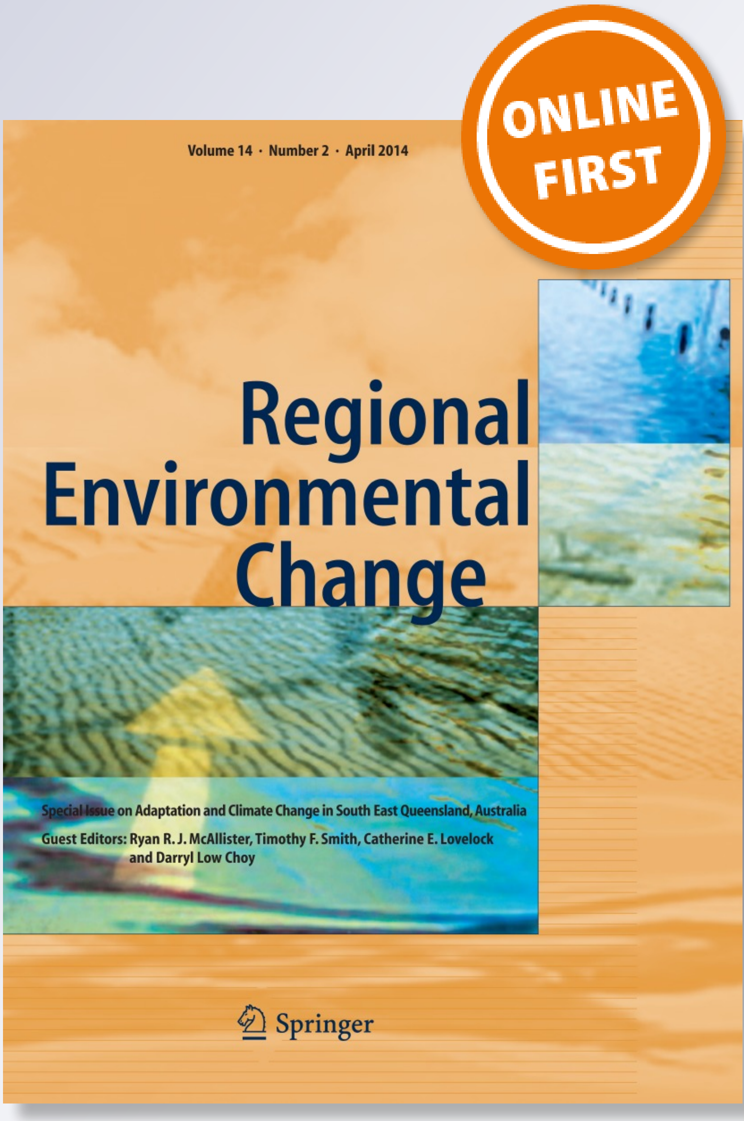
Regional Environmental Change

ISSN 1436-3798

Reg Environ Change
DOI 10.1007/s10113-014-0608-x



Springer

Reg Environ Change
DOI 10.1007/s10113-014-0608-x

ORIGINAL ARTICLE

Agricultural adjustment, population dynamics and forests redistribution in a subtropical watershed of NW Argentina

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Received: 12 April 2013 / Accepted: 9 March 2014

Abstract Patterns of land-use and land-cover change are usually grouped into one of two categories defined by the dominant trend: (1) deforestation resulting from expanding agriculture and (2) forest expansion, usually related to the abandonment of marginal lands. At regional scale, however, both processes can occur simultaneously even in the absence of net change. Given the focus on net change, such redistribution of agricultural and natural and seminatural lands has been generally overlooked. The interaction between agriculture modernization, human demography and complex topographic gradients of northwestern Argentina has resulted in processes of both forest recovery and deforestation, thus providing the opportunity to analyze patterns and driving forces of land-cover redistribution. We analyzed 20 years (1986–2006) of land-cover change in a subtropical watershed in relation to topographic and demographic variables. Although net forest change represented <1 %, forests redistribution affected 7 % of forest lands. There was a consistent geographic segregation of deforestation and forest recovery, with forests expanding over steep highlands and agriculture expanding over lowland irrigated areas. Population trends were not associated to forest expansion in lowlands but they explained 32 % of forest recovery in highlands. Highland forest expansion and lowland deforestation, respectively, imply conservation opportunities for humid montane forests and the environmental services they provide (e.g., watershed conservation) and threats for the conservation of dry forests and its biodiversity. Our study exemplifies the importance of land-use redistribution (rather than net change) with relevant environmental consequences at regional scale.

Keywords Land-cover change · Agricultural adjustment · Forests redistribution · Rural population · Rural migration · Forest transition

Editor: Helmut J. Geist.

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Introduction

Human land use is the main source of land-cover change (Foley et al. 2005). Deforestation has been largely recognized as one of the primary causes of global environmental degradation (Geist and Lambin 2002) over the last century; while forest recovery represents an opportunity to lessen overall forest losses. The shift from contracting to expanding forests due to the progressive adjustment of agriculture to land capability (i.e., agricultural adjustment) has been defined as forest transition (Mather 1992), which appears to be largely associated to socioeconomic development (Walker 1993; Mather and Needle 1998; Redo et al. 2012).

Demographic factors such as natural population growth and migration are often assumed to be important drivers of land-use and land-cover change (Mather and Needle 2000; Geist and Lambin 2002): In many regions, agriculture expansion has traditionally been driven by local population growth and immigration (Geist and Lambin 2001; Carr 2004; Izquierdo et al. 2011). However, modern agriculture practices linked to global markets are less dependent on

Published online: 06 April 2014

local population and more subjected to external economic agents, and population flows in these contexts could be a consequence rather than a cause of deforestation. Nevertheless, in Argentine dry Chaco forests, no association between deforestation and migration rates has been found (Paolasso et al. 2012). Forest recovery, contrastingly, has been hypothesized as driven by population losses, particularly rural out-migration (Mather and Needle 1998; Aide and Grau 2004). Socioeconomic development leads to better opportunities in non-farm jobs, threatening the competitive performance of subsistence agriculture in market-oriented economies and consequently pulling rural population off of marginal lands, potentially enabling the conversion of those lands into forest or other natural ecosystems (Wright and Muller-Landau 2006; Grau and Aide 2008). Quantitative assessments of the relationship between forest cover and population trends, however, remain scarce, particularly at the local scale of analysis; even though local spatial scales might be expected to yield clearer patterns (Mather and Needle 2000).

The causes and underlying drivers of both deforestation and forest recovery have been well documented both in developed and developing regions, from global to subregional scales (e.g., Geist and Lambin 2002; Grau et al. 2005a; Rueda 2010; Aide et al. 2013). Demographic and economic contexts and political and institutional structures are strongly associated with both deforestation and reforestation trends, although, in most cases, synergies and feedback occur, and multiple factors rather than single variables best explain land-cover change (Geist and Lambin 2002; Rudel et al. 2005). Most regions or countries present a significant environmental heterogeneity, including gradients in biophysical features such as topography, soils types and water availability. Such heterogeneity influences the composition and structure of forests as well as the potential for land use. Environmental heterogeneity frequently generates a spatial partitioning of ecological and socioeconomic processes, giving the opportunity to both deforestation and forest regrowth to simultaneously occur (Redo et al. 2012; Aide et al. 2013). Agricultural adjustment appears to be not only a driver of forest transition (i.e., the reversal of a trend in net change) but also a conditioning factor of forests redistribution. Since emerging and disappearing forests typically differ in biodiversity and their capacity to provide environmental services, the redistribution of forests potentially implies major environmental consequences (Grau et al. 2008; Redo et al. 2012). However, simultaneous analyses of both forest losses and regrowth trends remain scarce.

Northwestern Argentina is representative of the patterns and processes characteristic of land-use change in Latin America, having experienced both processes of deforestation and of forest recovery. Expanding national and international markets and technological changes led to increases in deforestation rates over the last decades, particularly in the lowlands of the dry Chaco forests and Yungas piedmont, which are being replaced by mechanized agriculture fields (Grau et al. 2005; Gasparri and Grau 2009; Gasparri et al. 2013). In contrast, in mountain areas not suitable for modern mechanized agriculture, rural population has been generally decreasing during recent decades (Izquierdo and Grau 2009), and land abandonment has led to forest recovery (Grau 1985; Grau et al. 2008; Araoz and Grau 2010, Carilla and Grau 2010). These two contrasting trends, however, have been studied separately both in terms of patterns and drivers.

In this paper, we conducted a spatially explicit analysis of forest cover change and population change in an area that covers most part of a subtropical watershed in northwestern Argentina, including both lowland dry forest and montane humid ecosystems. Specifically, we (1) quantitatively described land-cover change between 1986 and 2006, (2) identified the relationship between topographic features (altitude and slope) and moist and dry forest gains and losses and (3) explored dry and moist forests spatial and temporal dynamics in associations with net population change and immigration trends.

Methods

Study area

Our study was carried out in the Department of Trancas, Tucumán, Argentina (Fig. 1). The department (286,200 ha) includes most of the Tapia-Trancas watershed, a semiarid tectonic basin limited by Cumbres Calchaquíes range in the west and Medina mountain range in the east; spanning over an altitudinal range from 700 to 4,500 masl. Such a steep topographic gradient results in wide ranges of temperature and rainfall; from 300 to 600 mm/year and c. 18 °C in the lowlands to 600–800 mm of annual rainfall in the mid-elevation mountain slopes; and <0 °C of mean annual temperature at the top of the Cumbres Calchaquíes. As a consequence, the area includes three main ecoregions: (1) dry Chaco forests occupies the central lowlands and eastern (west facing) mountain slopes; (2) Yungas humid montane forests are located in the east-facing slopes of the Cumbres Calchaquíes (approximately between 1,000 and 2,500 masl in the central-western belt of the study area), and (3) high-elevation grasslands, above 2,500–2,700 masl in the west side of the basin). The region has experienced an increase in rainfall since the late 1950s (Minetti and Lamelas 1997) .

Given that in most of the agriculture area mean annual evapotranspiration (900 mm/year) exceeds rainfall, the area experiences water deficit, and agriculture is partially

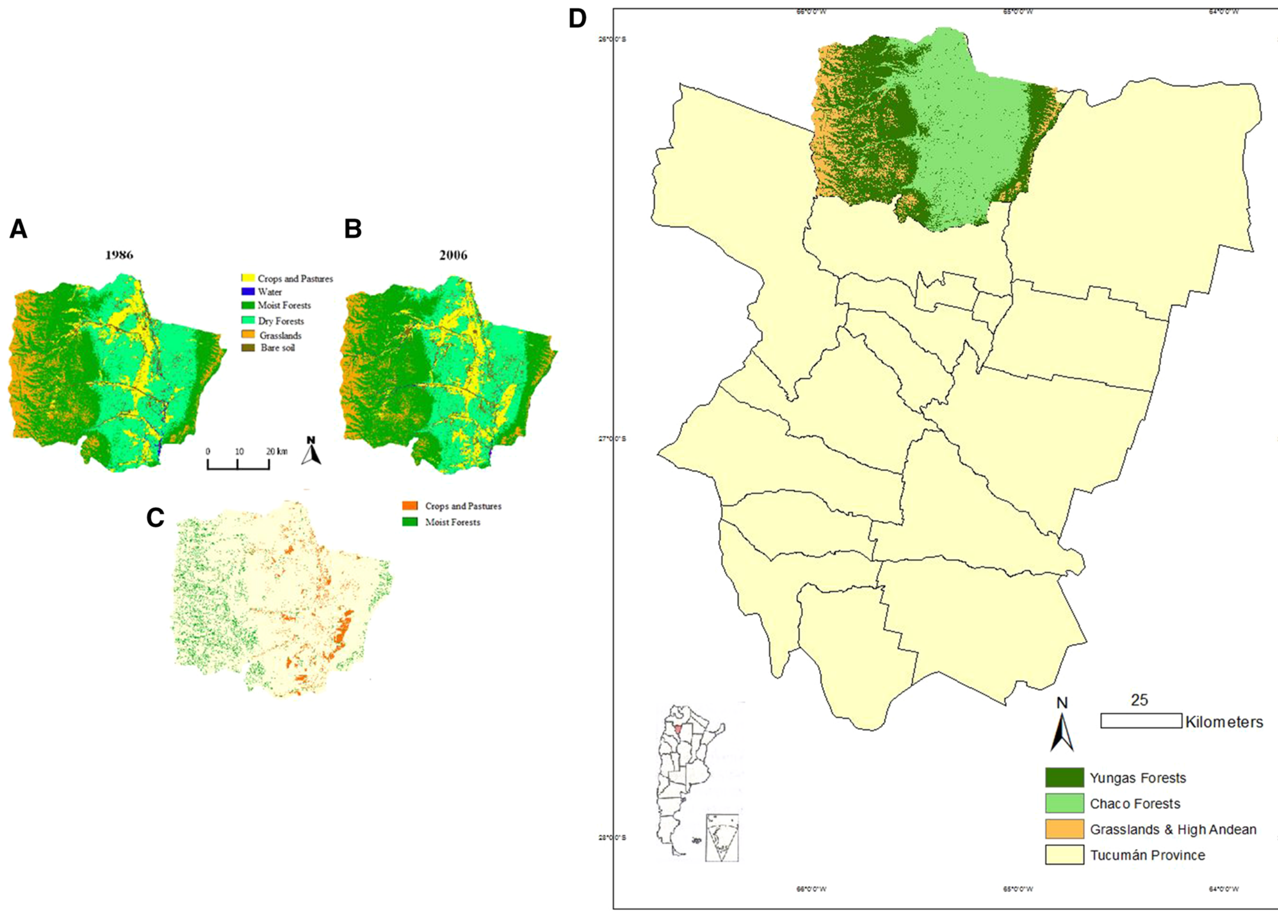

Fig. 1 Land-cover maps for 1986 (**a**) and 2006 (**b**): and map of "new" crop and pastures and moist forests (**c**). **d** represents the relative location of the study area within the province limits and its main ecoregions

limited to irrigated areas in the lowlands, particularly in winter (i.e., Chaco ecoregion and Yungas Valley). Historically, the main agriculture activity has been cattle raising, mostly for milk production for local consumption, based on a combination of irrigated forage crops such as alfalfa and sorghum, and free-ranging foraging in the natural environments. Medium-scale agriculture production and most populated centers concentrate in the lowlands, near the main roads and rivers. In 1990, milk production in the area underwent an enterprise crisis which resulted in (1) a partial shift from cattle rising to other agricultural activities such as fruit and vegetable crops production in irrigated fields and rainfed black beans for exports to international markets (from 7,200 ha in 1999 to 12,000 ha in 2008; EEAOC 1999, 2008), and (2) restructuring of the dairy industry in the region enhanced by provincial and national policies, which led to a change from local subsistence to national oriented production (Cisint 2004; Dirección de Ganadería de la Provincia de Tucumán. SAAyA 2006) and to the expansion of perennial foraging crops (from 3,691 ha in 1988 to 8,971 ha in 2002) particularly alfalfa and buffel grass (Censo Nacional Agropecuario 1988, 2002). The region therefore experienced an overall shift from subsistence, small scale to intensive larger-scale agriculture production that had resulted in agriculture expansion in the area.

Between 1980 and 2001, total population increased, but rural population decreased from 11,270 to 9,693 inhabitants INDEC (1991, 2001). Total population dynamics include local migration of the dispersed population toward the main villages, foreign (Bolivian) immigration for horticulture activities and out-migration to large urban centers outside the study area (Garrido 2005). Dispersed rural population tends to practice subsistence activities such as goat and sheep ranching (Garrido 2005) and subsistence livestock (i.e., sheep, goats, and pigs) experienced major reductions from 1988 to 2002 (from 3,126 to 705, 3,122 to 1,584, and 4,222 to 1,927, respectively) (Censo Nacional Agopecuario, 1988, 2002).

Land-cover data and population

We produced land-cover maps for two dates, 1986 and 2006, based on Landsat Thematic Mapper (TM, 30 × 30 m pixel resolution) images from September, 11, 1986, and October, 23, 2006. The department of Trancas is included in two scenes (path 231, rows 78 and 79) which were subset with the department boundaries, and co-registered with the nearest-neighbor sampling method, using ENVI 4.2 software (co-registration error <0.5 pixels). The supervised classification was performed with the random forest (RF) algorithm (Breiman 2001), using "random forest" (Liaw and Wiener 2002) and "sp" (Pebesma 2005) packages in R software. RF is an ensemble classifier that consists of many decision trees and that, for each pixel, outputs the class that is the mode of the classes output by individual decision trees.

The land-cover categories selected for the supervised classification were as follows: moist forests, dry forests, bare soil, and natural grasslands. For each class, we assigned training sites (approximately 300 per class) taken in the field in order for the decision trees to classify each pixel as a function of satellite band values and altitude derived from a digital elevation model. Crops and planted pastures were digitized manually because RF algorithm tended to confound them with bare soil, and they were included in the same category, representing agricultural area. To assess the precision of the classification, we used 388 ground control points taken in 2012 for all classes distributed along the study area, in order to generate a confusion matrix for 2006 land-cover map. We used Google Earth® high resolution scenes (e.g., Quickbird, Spot) from 2004 to 2011 to guarantee that the ground control points belonged to the same land-cover category in 2006 and in 2012. The overall accuracy obtained was 96, 3 %, and there was essentially no error in discriminating between forested and non-forested land-cover categories (Table 1).

Population changes in the Department of Trancas were assessed by analyzing data from two national population censuses conducted in between the two land-cover dates (INDEC). We used the finest spatial scale available in the census since 1991, which is the "censal unit." Each censal unit comprehends at least 30 households and is spatially defined although variable in size. The Department of Trancas includes 35 censal units, which were digitalized using ArcGIS software. For each censal unit, we considered the following demographic variables: "total population' in 1991 and 2001 in order to derive population change," and "number of people who lived in a different place 5 years prior to 2001," as an index of immigration. Unfortunately, there is no data at the censal unit scale to derive rural out-migration but we assumed that negative population change in a given censal unit reflects (in a conservative way) net out-migration, since natural population change is expected to be positive in the area. To discriminate natural population growth and out-migration from immigration changes, we additionally computed the "non-immigratory population change" (NIPC) as [("total population in 2001"—"total population in 1991")—(number of people who lived in a different place 5 year prior to 2001 * 2)]. We multiplied it by two since the immigration estimate covers a time span of 5 years, half the time of the inter-census period.

The relationship between forest cover change and topography was assessed by analyzing changes in both dry and moist forest cover in relation to altitude and slope. A digital elevation model derived from SRTM 90 m Digital Elevation Database version 4.1 (Jarvis et al. 2008) was used to classify slope in four categories (0–25, 25–50, 50–75, and 100 %). Then, the number of pixels converted to agriculture and the number of pixels converted to forest were calculated for each slope category. Percent of dry and moist forest change was calculated for four altitude categories (500–750, 750–1,000, 1,000–1,250, 1,250–1,500; and 900–1,500, 1,500–2,000, 2,000–2,500, 2,500–3,000 masl for dry forests and moist forests, respectively).

To assess for the relationship between forest cover change and demographic trends, we performed a multiple linear regression analysis between net forest cover change

Table 1 Assessment of the accuracy of the land-use classification for 2006 by verification using ground control points taken in the field

Image classification	Ground points					
	Dry forests (DF)	Moist forests (MF)	Crops and pastures (CP)	Grasslands (GL)	Bare soil (BS)	Water
Dry forests	83	–	–	–	–	–
Moist forests	1	60	–	–	–	–
Crops and pastures	–	–	80	–	–	–
Grasslands	–	–	–	79	–	–
Bare soil	–	–	–	–	52	–
Water	–	–	–	6	3	24
Total	84	60	80	85	55	24
Accuracy (%)	98.8	100	100	92.9	94.5	100
Total accuracy (%)			**96.3**			

as the dependent variable and both immigration index and NIMC as independent variables. Previously, we tested the colinearity between population variables and found they were not correlated. We also performed simple linear regression analyses between both demographic variables and forests gains and losses separately, in order to analyze their association with each forest trend in particular. Previously, all variables (forest cover change, 1991–2001 population change and immigration index) were relativized as a proportion of the total in 1986. Censal units that corresponded to the main villages (i.e., >1,000 inhabitants) were not considered in these analyses because their percentages of forest cover were in most cases equal to zero, which left a total of 33 censal units analyzed. We also performed a Kruskal–Wallis test to evaluate whether population change and number of immigrants change medians significantly differed between censal units that, respectively, gained or lost forest cover.

Results

Between 1986 and 2006, the total area of forest cover decreased by 0.9 % (−2,139 ha). This apparently low level of forest change, however, is the result of much larger and opposite-direction changes in the two types of forests. While dry forests decreased by 10,243 ha, (4.6 and 9.9 % of total forest cover and dry forest cover, respectively), moist forests increased by 8,104 ha (3.6 and 6.8 % of total forest cover and moist forest cover, respectively (Fig. 2, Table 2). In other words, while net forest change represented <1, 7 % of the "original" forest cover was "relocated" from lowlands to mountain slopes. The decrement of dry forests was mainly due to their conversion to cultivated area (pastures and agriculture), while moist forests regrew over grasslands.

While virtually all pixels converted to agriculture occured in areas with <25 % slope and <1,000 m of elevation, (Fig. 2a,c), new forests regrew mostly above 1,500 m of elevation and 25 % of slope. There was also no deforestation above the elevation at which forest expansion peaked (Fig. 2b, d).

From 1990 to 2001, the total population in the Department of Trancas increased by 3,496 people (23.3 %), but this growth occurred mostly in the main settlements, and at the department scale, rural population declined by 181 people (2 %). However, when the finer scale of "censal unit" was analyzed, more complex population dynamics emerged: 18 of the 35 censal units decreased in their populations (i.e., experienced out-migration); while population increased in 17. The number of immigrants (i.e., people who lived in a different place 5 years prior to 2001) also varied considerably and tended to be higher in censal units that corresponded to the main rural villages or to their surroundings (Fig. 3).

Table 2 Land-use transition matrix (in hectares) for the period 1986–2006

	Moist forests	Dry forests	Crops and pastures	Grasslands	Total in 2006
Moist forests	104,147	6,068	381	14,614	125,684
Dry forests	4,553	81,799	2,998	0	93,102
Crops and pastures	1,755	8,191	23,432	425	37,112
Grasslands	5,714	0	0	23,966	29,877
Total in 1986	117,580	103,345	29,756	39,419	

Rows represent the land-use category in 1986 (top) and the status of the areas in 2006 (bottom). Columns represent the land-use categories in 2006 (left) and the status of the areas in 1986 (right)

In the multiple regression analysis, immigration and out-migration explained 25 % of total forest cover change ($p < 0.01$). Rural censal units of net forest expansion and net forest decrease, significantly differed in their relative number of immigrants ($H = 4.07$; $p < 0.05$) (Fig. 4c) but not in their NIPC ($H = 0.32$; $p = 0.57$). However, when the relationship between population and forest trends was analyzed for both kind of forest changes separately, different patterns emerged: neither NIPC nor immigration were associated to forest losses ($R^2 = 0.04, p = 0.22; R^2 = 0.02, p = 0.56$, respectively), while forests gains were significantly and negatively related to NIPC ($R^2 = 0.32$, $p = 0.01$) but not to immigration ($R^2 = 0.01$ $p = 0.88$).

Discussion

Total forest cover remained relatively stable between 1986 and 2006 in the study area, with <1 % of net change. However, this seemingly stable figure masks an important process of land-cover redistribution. Such complex land change pattern becomes clear when both types of forests are considered separately, as the expansion of moist forests over grasslands offsets most dry forests conversion into crops and pastures in lowlands (Fig. 1, Table 2). Socio-economic development, including transport and irrigation infrastructure, appears to be the main driving force of deforestation in lowlands and, as an unintended side effect, of forest recovery in highlands, since the region experienced a shift from local subsistence to market-oriented agriculture practices in the last decades, which led to the expansion of cropped land for food, one of the most robust causes of deforestation globally (Geist and Lambin 2002).

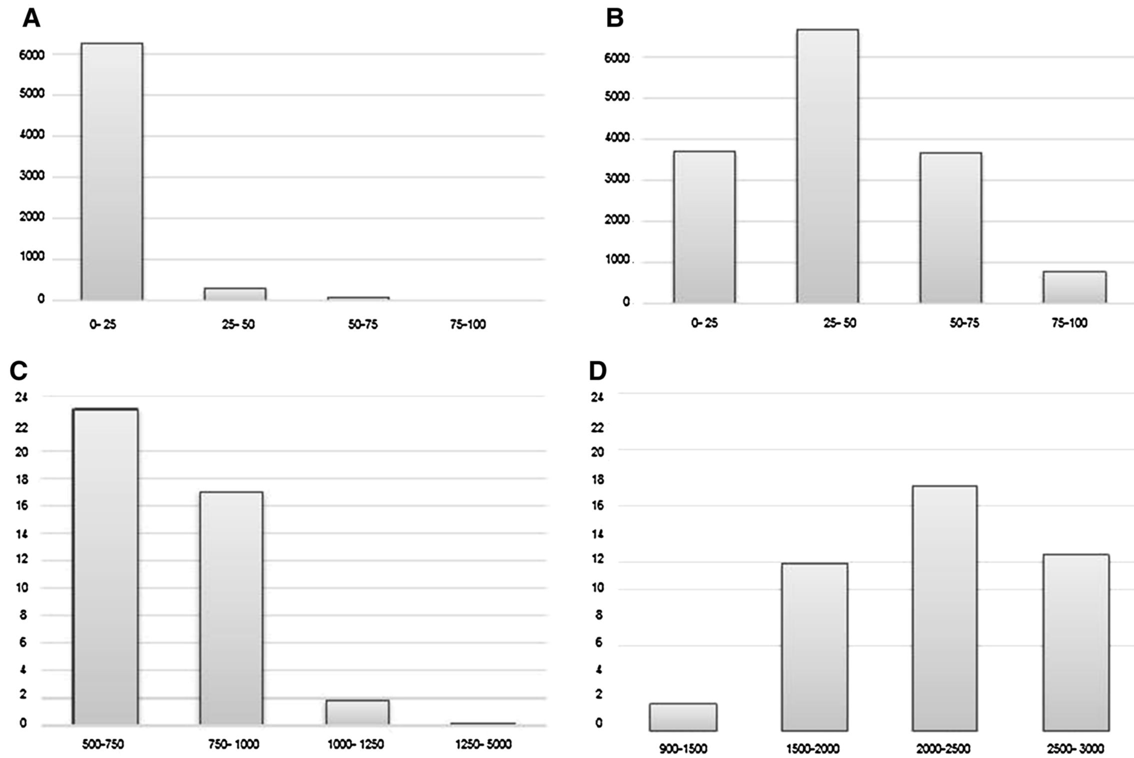

Fig. 2 Number of pixels (*X axis*) **a** converted to agriculture, **b** recovered to forest in relation to % of slope. Percentage of land (*X axis*) converted to **c** agriculture and **d** forests in relation to altitude

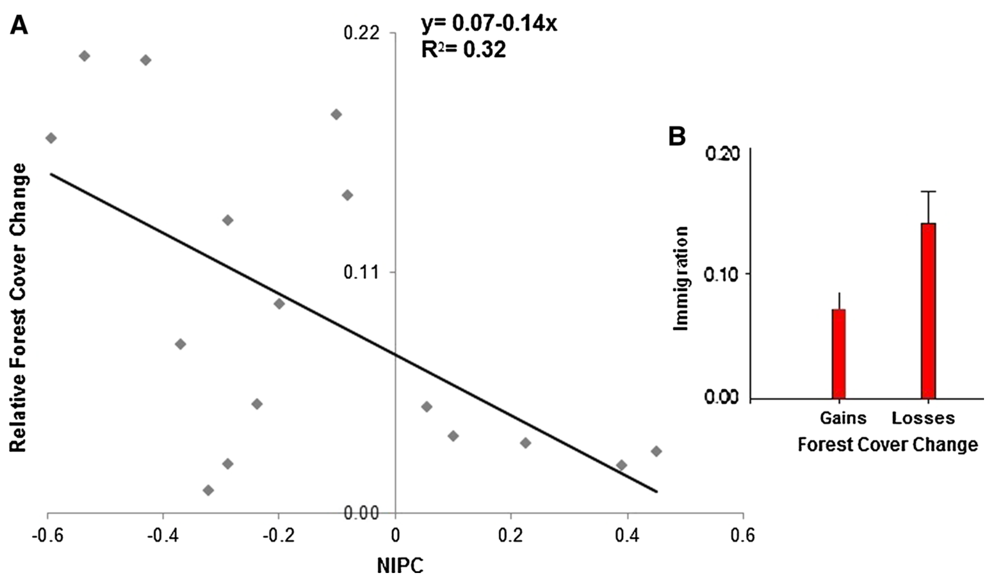

Fig. 3 **a** Relationship between relative values of forest cover change (Y) and relative values of NIPC. *Lines* represent linear regression. **b** Relative number of immigrants in censal units experimenting forest losses and gains

Similar asymmetries in forest cover change characterized less developed countries in Central America, where both rapid deforestation and forest regrowth can be found according to the biome or ecoregion (Redo et al. 2012). Geographic heterogeneity is a key factor in the relocation of forests because different slope, soils, and climate conditions determine the potential for agriculture productivity and mechanization. In our study area, the spatial segregation of deforestation and forest recovery is mainly due to the topographic gradient of the area, as it is the natural differentiation of dry and moist forests. Our analyses relating slope and altitude to forest gains and losses show that moist forests in high-elevation steep lands are not threatened by deforestation, which concentrates in dry

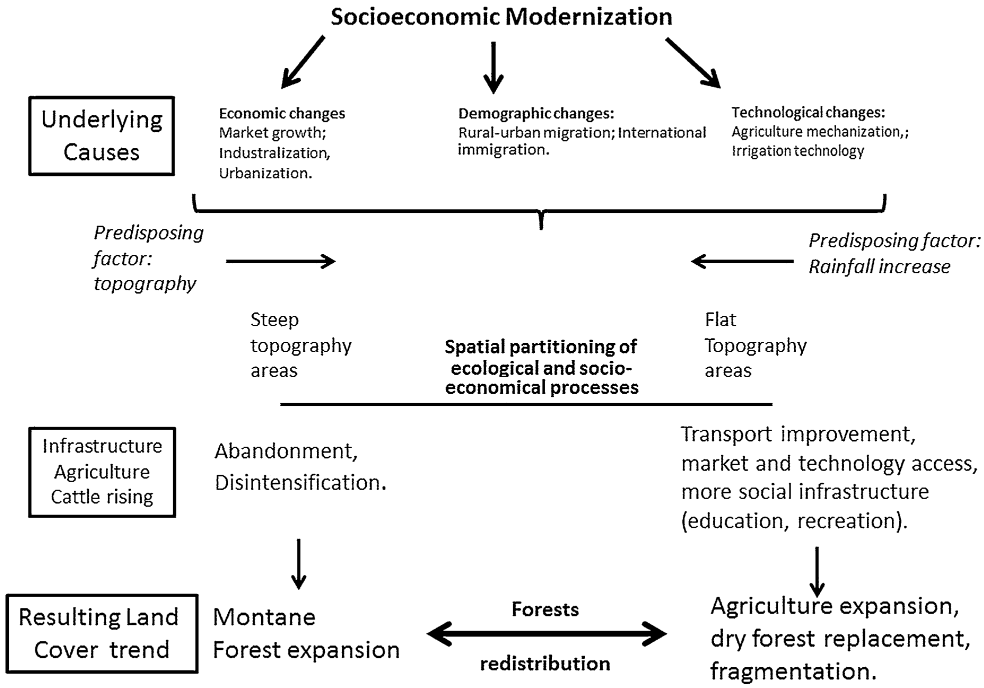

Fig. 4 Conceptual figure showing the main underlying causes of both montane forest expansion and dry forest replacement, which ultimately leads to the redistribution of forests

forests in lowlands. In fact, despite lower natural primary productivity due to more arid conditions, dry forest areas are more suitable for conversion due to the low slope inclination, which allows mechanization and irrigation. These differences in agriculture potential also direct population migration toward the lowlands, where the main settlements and economic opportunities can be found, thus promoting land abandonment in montane areas.

Trends in population between 1991 and 2001 in our study area mirror the situation of many areas of Latin America and the globe, where although total population increases, rural population declines (Dufour and Piperata 2004). Our study area as a whole can be generally considered a rural area, since overall population density is low and human settlements are relatively small and sparse villages. Within this rural population, however, there appears to be a shift from subsistence agriculture to market-oriented economic activities that can be illustrated by the important reductions in subsistence livestock. “Rural–rural migration” (toward more densely populated rural areas) may share the same characteristics with rural–urban migration, including the benefits for immigrants such as better education, health and labor opportunities (Aide and Grau 2004), with perhaps the advantage of a more gradual change in their life style. Total forest cover change presented a negative association with population change and immigration. However, when analyzed separately, deforestation in lowlands was not associated with demographic variables, suggesting demographic trends are neither a driver nor a consequence of deforestation processes per se. These results are consistent with analyses conducted for the whole Chaco region, which show that linkages between agriculture and demographic processes in this expanding market-oriented agriculture region are weak (Paolasso et al. 2012). Socioeconomic changes might have leaded to agriculture expansion in lowlands on the one hand and to immigration on the other, since population tends to migrate to the main local settlements and areas of irrigated labor-demanding horticulture, which are, too, located in low altitudes. Therefore, the fact that immigration is significantly higher in censal units that lost forest does not imply causality but rather that they are both driven by the same underlying factor, which goes unperceived if only total forest cover is considered. Forest gains, however, were importantly related to NIPC, this variable explaining 32 % of forest recovery. This suggests that the reduction in the number of inhabitants, probably due to dispersed population out-migration, and ultimately driven by socioeconomic changes, does indeed lead to forest recovery in highlands through its effect on land abandonment and disintensification. Population out-migration implies reductions in subsistence livestock in grasslands (particularly sheep and cattle), and land abandonment, facilitating forests encroachment, as observed in the study area and other similar montane areas of northwestern Argentina (e.g., Grau and Veblen 2000; Araoz and Grau 2010; Carilla and Grau 2010).

Demographic and socioeconomic trends are drivers of forests relocation within the study area, and topography (through its effect on mechanized agriculture suitability) is the key biophysical factor conditioning their new distributions (Fig. 4). In addition, regional climate change (rainfall increase, Minetti and Lamelas 1997) might have also influenced these forest cover trends. Water availability for irrigation is a limiting factor for agriculture in the area and higher rainfalls could be associated with agriculture expansion in lowlands. A total of 6,068 hectares of dry forests in 1986 were classified as moist forests in 2006 (Fig. 4, Table 1), suggesting a progressive change in forest composition toward more evergreen forest types, characteristic of humid conditions. In addition, rainfall increase could have facilitated the expansion of both irrigated (through more water availability in the dry season) and rain-fed agriculture, such as soybean and black beans. Woody encroachment over grasslands in montane areas is also favored by increasing rainfalls, particularly in case of water demanding species such as *Alnus acuminata* (Araoz and Grau 2010) which is one of the most important tree species expanding in highlands. In summary, by both facilitating forest expansion in highlands and agriculture expansion in lowlands, regional rainfall increase could have favored land-cover redistribution.

Addressing environmental heterogeneity and discriminating among different types of forests allow perceiving environmentally relevant land-cover change patterns that would remain hidden when only net changes are considered. Historically, forest transition literature has mostly focused in the potential of forests recovery to lessen the effects of deforestation, which has mostly been measured through the capacity of secondary forests to sustain diversity and ecosystem services (e.g., Rudel et al. 2002; Chazdon et al. 2009; Nagendra and Southworth 2010). But the natural heterogeneity that allows agricultural adjustment and therefore forest transition to occur almost necessarily implies the spatial redistribution of forests; these redistributions can have even more important environmental consequences than net forest cover changes. Thus, by being spatially segregated, certain types of forests end up replacing others in the long term, and forest transition appears to be a process of forest redistribution and replacement upon which the final forest balance depends. In this sense, perhaps more important than the comparison between mature and secondary forests, and more significant for conservation initiatives, is the identification of opportunities and risks of the replacement between different types of ecoregions or biomes (e.g., Redo et al. 2012; Aide et al. 2013), which differ in species composition and in their capacity of providing ecosystem services. For example, the redistribution of forests implies changes in carbon stocks, because different forests compositions accumulate different biomass quantities, as well as changes in watershed protection, since new forests occur under different climate and topography than disappearing ones.

In our study case, as it occurs in many places of Latin America and the world (Redo et al. 2012; Aide et al. 2013; Hansen et al. 2013), forest recovery largely compensates for forest losses. Socioeconomic development drives agriculture expansion in lowlands and promotes, in turn, development of transport, housing and agriculture infrastructure and further, encouraging population to settle in these areas. On the other hand, rural out-migration, derived as well from socioeconomic changes, promotes forest recovery in highlands, altitude, and slope conditioning the opposite trajectories of these processes (Fig. 4). Although net forest change was close to zero in the study area, it does not imply forest stability at all. In a temporal window as short as 20 years, 10 % of dry forests were lost while moist forests increased by 7 %, implying major ongoing changes. The recovery of moist montane forests over areas of higher rainfall and steeper slopes imply a potentially significant improvement in watershed protection, with the advantage that the current and most likely future demographic and socioeconomic trends reduce the potential for conflicts between conservation and production activities. Dry Chaco forests and humid Yungas forests below 1,500 masl, in contrast, become the most threatened ecoregions in the context of forest redistribution and agricultural adjustment, with several risks involved, such as the loss of important ecotones between Chaco and Yungas along with its associated biodiversity (Brown et al. 2002). As long as agricultural adjustment toward easily mechanized and irrigated areas remains as the main driver of land-use change, it is likely that forests that recover will differ from those that disappear, and that specific threats and opportunities for specific types of forests emerge, which emphasizes that this concept goes beyond the shift from net deforestation to net reforestation. Spatially explicit analyses of forest change clearly indicate that frameworks of forests redistribution, rather than net forest change, can become a practical approach for setting up conservation priorities and regional land-use policy aimed at the improvement of ecosystem services.

Acknowledgments We thank N. Ignacio Gasparri at Instituto de Ecología Regional, Tucumán, Argentina, for his assistance with satellite image analysis. This research is funded by Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) and Rufford small grants for nature conservation grants for the first author's PhD project "Land use change and ecosystem services provision in a subtropical watershed."

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