Research

Long-Term Forest Dynamics and Land-Use Abandonment in the Mediterranean Mountains, Corsica, France

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ABSTRACT. Human practices have had an impact on Mediterranean ecosystems for millennia, particularly through agricultural and pastoral activities. Since the mid-19th century, land-use abandonment has led to the expansion of shrubland and forest, especially in the mountainous areas of the northern Mediterranean basin. Knowledge of these factors is vital to understanding present forest patterns and predicting future forest dynamics in the Mediterranean mountains. We aimed to analyze and understand how land-use abandonment affected spatial modifications of landscapes in two study areas, 44,000 ha and 60,000 ha, located on the island of Corsica, France, representing a typical Mediterranean environment with chestnut forests. Our approach used land-cover archive documents from 1774, 1913, 1975, and 2000, and human population history, 1770 to present day, to describe landscape patterns following land-use abandonment. This research showed that dramatic changes in landscape at the two study areas were caused by the suspension of human influence and the interruption of traditional farming practices. Over the study period, both study sites showed significant reforestation of shrubland and cultivated areas marked by the presence of *Quercus ilex* forests (+3.40% yr-1 between 1975 and 2000) and by *Pinus pinaster* (+3.00% yr-1 between 1975 and 2000) at one study site that had experienced heavy rural exodus. At the same time, areas containing chestnut forests decreased by 50% between 1774 and 2000 (-0.09% yr-1 between 1774 and 1975 and -1.42% yr-1 between 1975 and 2000). Shrubland expansion remained limited at both study sites. Our study highlights the value of small-scale approaches for understanding the ecological consequences of land-use abandonment and present and future land-management decisions. Discussion concludes on the importance of working with long-term series for studies on resilience in social-ecological systems and on the consequences in terms of provision of ecosystem services.

Key Words: *historical archives; human population; landscape patterns; land-use change; Mediterranean ecosystems*

INTRODUCTION

The abandonment of agricultural land has been a widely observed trend in the Mediterranean mountains since the early 19th century (Walther 1986, Garcia-Ruiz and Lasanta-Martinez 1990, Blondel and Aronson 1999, MacDonald et al. 2000, Romero-Calcerrada and Perry 2004). The commercialization of agriculture through technological development combined with increasing off-farm employment opportunities arising from the industrialization and urbanization of accessible lowland areas has motivated many mountain farmers to migrate, either temporarily or permanently. Depopulation and land abandonment essentially reflect an inability to enhance the productivity of traditional agriculture because of fragile mountain environments, reduced economies of scale because of highly fragmented and diversified biophysical conditions, and resistance to the adoption of modern, market-oriented farming practices (MacDonald et al. 2000). Land-use changes are the main processes shaping land-cover variation, ecosystem dynamics, and shifting landscape patterns.

The re-establishment of natural species on abandoned agricultural land is a common land-use change in the northern rim of the Mediterranean basin (Debussche et al. 1999, Mouillot et al. 2005, Chauchard et al. 2007) and has led to the expansion of scrub and forest and a decrease in many seminatural open habitats in the Mediterranean mountains that had previously been maintained by traditional practices (Marty et al. 2003). The intensity of this mountain area revegetation has had several negative consequences, including greater risk of fire and an increase in the speed at which wildfires spread (Vázquez and Moreno 1998), reduced water availability (Gallart and Llorens 2004), a reduction in landscape quality and agricultural value (Vos and Meekes 1999), a reduction in the extent of pastoral areas (Molinillo et al. 1997), and a reduced spatial distribution of rare or endemic species (Farina 1997, Preiss et al. 1997, Labaune and Magnin 2002, Kiss et al. 2004).

In this context, Europe's regional administrations have introduced specific measures to promote the regeneration of these lands, i.e., prevent abandonment and facilitate forest restoration (Pereira et al. 2005, Lasanta et al. 2009). Sustainably managing these lands requires a historical understanding of the chronology and mechanisms shaping woodland expansion to support targeted regional planning. The main goal of such planning is to evaluate landscape dynamics at appropriate spatial and temporal scales, giving special focus to factors and processes that influence landscape change. It is necessary to analyze the socioeconomic changes that have occurred since the 18th century to estimate their

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influence on present-day forest cover and dynamics (Agnoletti 2007). Proper analysis of ecosystem dynamics hinges on using local land-use and socioeconomic history.

Few studies have attempted to analyze and understand the interactions between historical spatial changes and land-use abandonment in Mediterranean landscapes because of the scarce data available. Understanding these interactions would help clarify unresolved questions on the interrelated effects of land abandonment and long-term Mediterranean vegetation dynamics. This study set out to find answers by rebuilding land-cover dynamics and land-use abandonment through human population history over a period long enough to reflect on both land-use changes and intrinsic successional processes. Two study areas, located on the island of Corsica, France, Mediterranean Sea, (Fig. 1) were considered in relation to chestnut presence and to the populations involved. These two sites were similar in area, elevation, relief, and climate, but different in terms of landscape and population activity. The first site, San Petrone massif, is characterized by large chestnut groves and a high population density. The second site, Vico-Evisa region, has more pastoral activity and a low population density. Both sites have experienced a significant decline in population since the last century.

Fig. 1. Location of Corsica in the western Mediterranean region. The study areas (black lines) are indicated on the topographical map.
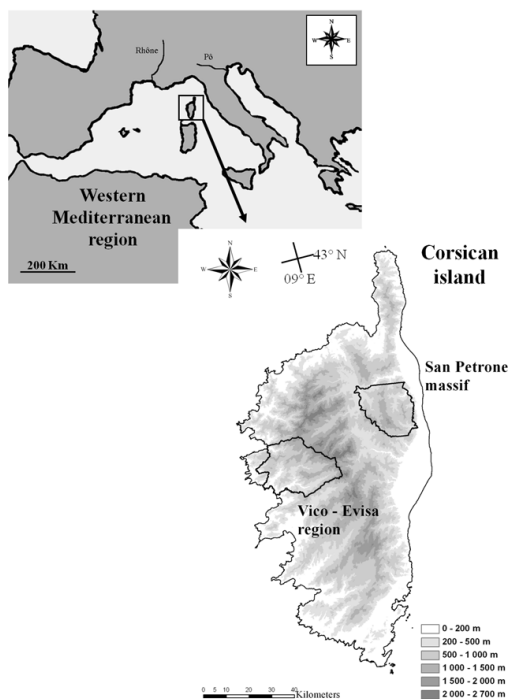
MATERIAL AND METHODS

Study areas

The study was performed on the island of Corsica, which is located in the western part of the Mediterranean region. Corsica is the woodiest island of the Mediterranean Sea, with forests covering 46% (401,817 ha) of the island's total 872,608 ha area (Inventaire Forestier National 2006). The topographic, geological, and climatic conditions, together with the influence of the sea, facilitate the installation of vegetation, resulting in forests that are frequently dense. Corsica is part of the Mediterranean climate zone with subtropical, temperate, or alpine affinities depending on season and altitude. Corsica's highly mountainous terrain produces significant climactic contrasts. The dominant species are the maritime pine (*Pinus pinaster* Ait.), holm oak (*Quercus ilex* L.), chestnut (*Castanea sativa* Mill.), Corsican pine (*Pinus nigra* Arn. ssp. *laricio* (Poir.) Maire var. *corsicana*), beech (*Fagus sylvatica* L.), and cork oak (*Quercus suber* L.; Inventaire Forestier National 2006). Two study areas were selected, San Petrone massif and the Vico-Evisa region (Fig. 1), similar in area, elevation, relief, and climate, but different in terms of landscape (Table 1). However, in both areas, chestnut trees have an impact on the local population's activities.

Historical land-cover reconstruction

The first map of Corsica, Plan Terrier, was ordered in 1774 by Louis XV of France to inventory the natural resources of the island after its acquisition (Caratini 1995). A precise map at a 1:10,000 scale was consequently published (Albitreccia 1942). The Archives départementales de Corse du Sud delivered six scanned maps for the two study areas. Each map was georeferenced using ArcGis version 9.3 (ESRI®). Confluence and ridge lines were used as basepoints for georeferencing the map with Lambert 4 coordinates; for each scanned map, 20 basepoints were used on the whole landscape. Land-cover patches are represented by polygons on a schematic topographic background. The polygons were redrawn in vector format by tracing the lines of the scanned and georeferenced maps. For San Petrone massif, each polygon was assigned to one of seven land-cover types used in the map (Table 2). For the Vico-Evisa region, each polygon was assigned to 1 of 13 land-cover types used in the map, which correspond to combinations of the 7 land-cover types in the Plan Terrier (Table 2). We aggregated woodlands and chestnut forests into a generic 'forests' land-cover type, and olive trees, vineyards, and crop cultivations into a generic 'cultivated areas' land-cover type. We consider the four generic land-cover types, forests, shrublands/grasslands, cultivated areas, and urban areas, used as a common classification for long-term translation across time (Table 2). The maps were converted to raster format at a 100-m resolution in a GIS database.

Table 1. General characteristics of the two study areas.

Study areas	San Petrone massif	Vico-Evisa region
Geographical coordinates	42°19' N, 9°20' E	42°12' N, 8°46' E
Surface area (ha)	43,875	60,409
Elevation (m)	80 to 1767	0 to 2200
	(40% of the study area is between 500 and 700 m)	(40% of the study area is between 400 and 900 m)
Climate	Mediterranean mountain	Mediterranean mountain
	(warm and dry in the summer / cold and snowy in winter)	(warm and dry in the summer / cold and snowy in winter)
Mean annual precipitation (mm)	942 ± 326	1271 ± 310
	(according to the Piedicrocce meteorological station [1952–1976] and the La Porta meteorological station [1977–2008])	(according to the meteorological station at Evisa [1955–2008])
Mean annual temperature (°C)	12.7 ± 1.3	12.5 ± 0.9
	(from 5.2 in January to 21.4 in August)	(from 5.7 in January to 22.4 in August)
	(according to the meteorological station [1980-2008])	(according to the meteorological station [1978-2008])
Substrate	Schist associated with rocks of oceanic origin	Granite covered by brown acid soils
	(Durand-Delga 1978)	(Roche and Roux 1976)
Landscape at the highest altitude	*Fagus sylvatica* pure and sometimes mixed with *Pinus laricio* or *Pinus pinaster* in the western massif border (Gamisans 1999)	*Pinus laricio* pure and sometimes mixed with *Fagus sylvatica* or *Pinus pinaster* in the lower fringe (Gamisans 1999)
Landscape at the lower altitude	*Castanea sativa* (introduced by humans; Pitte 1982, 1986) often mixed with *Alnus cordata*, *Quercus ilex*, moors, scrubland (e.g., *Cistus* sp., *Pteridium* sp., *Laburnum* sp.; Gamisans 1999)	Scrublands (e.g., *Cistus* sp., *Pistacia lentiscus*, *Myrtus communis*) and grasslands with scattered *Quercus ilex* or *Pinus pinaster*. *Castanea sativa* fairly common in this area with moors and ferns (*Pteridium* sp.). Valleys and littoral-zone coasts with different crops (Gamisans 1999)

An additional survey was conducted on the territory by the French fiscal services (Source: Archives départementales de Haute-Corse et de Corse du Sud; Corvol 1999). This survey provided landscape compositions for the year 1913, but in a nonspatial format. We used this for intermediate updates of landscape composition. We consider the four generic land-cover types as the common classification for long-term translation across time.

Present land-cover maps

Amandier et al. (1984) established a precise land-cover map of Corsica for 1975. Each map was built from 1:17,000 scale, color-infrared aerial photographs. Numerical vector maps with Lambert 4 coordinates were provided by Corsica's regional environment office. We assigned vegetation types to the remaining polygons, and 12 land-cover types were defined according to a vegetation layer-based typology developed by Godron et al. (1968) and Trabaud (1973) for Mediterranean vegetation (Table 2). Chestnut forests, coniferous forests, beech forests, mixed forests, riparian forests, and other broadleaf forests corresponded to dense or open forests with trees (height > 2 m) covering between 25% and 100% of the area, as described in Table 2. As defined in the map key, we considered the vegetation type mixed forests, which included undifferentiated coniferous and broadleaf forests in which *Castanea sativa* or *Fagus sylvatica* could be present. Shrublands, mixed shrublands/grasslands, and grasslands corresponded to nonforested land-cover types and were defined according to percentage cover of shrubs and herbaceous layers (Table 2). The vegetation types were aggregated into the four generic land-cover types for certain

analyses (Table 2). The maps were converted to a 100 m resolution raster format in a GIS database.

The National Forest Inventory established a precise land-cover map of Corsica for the year 2000 (Inventaire Forestier National 2006), built from 1:17,000 scale, color-infrared aerial photographs. Numerical vector maps with Lambert 4 coordinates were produced. We assigned vegetation types to the remaining polygons, and 12 vegetation types were defined according to a vegetation layer-based typology for Mediterranean vegetation (Godron et al. 1968, Trabaud 1973; Table 2). In the National Forest Inventory, chestnut forests, coniferous forests, beech forests, mixed forests, undifferentiated broadleaf forests, and other broadleaf forests corresponded to dense and open forests with 40% to 100% tree cover (Table 2). As defined in the National Forest Inventory legend, we considered mixed forests, which included undifferentiated coniferous and broadleaf forests, and undifferentiated broadleaf forests, all the broadleaf species in which *Castanea sativa* or *Fagus sylvatica* could be present. Shrublands, mixed shrublands/grasslands, and grasslands corresponded to nonforested land-cover types. Because this map had essentially been created based on the forest inventory, it did not define bare soils, cultivated areas, or urban areas. We assigned every polygon to these land-cover types using 1:25,000 scale, color aerial photographs that had been created by the Institut Géographique National in 2001. Polygon interpretation was therefore based on in situ field observations that were gathered in spring 2009. Using a GPS, we collected 149 field data points for the San Petrone massif and 122 field data points for the Vico-Evisa region to inventory maximum

Table 2. Generic land-cover types, definitions, and percentage cover of each vegetation layer for each map used.

Generic land-cover type	1774 (*Plan Terrier*)	Definition	1975 (Amandier et al. 1984)	Definition	2000 (Inventaire Forestier National, 2006)	Definition
Forests	Chestnut forests	Only *Castanea sativa*	Chestnut forests	Dense and open forests of *Castanea sativa* (tree layer > 2m = 25-100%; shrub and herbaceous layer < 2m = 0-100%)	Chestnut forests	Dense and open forests of *Castanea sativa* (tree layer > 2m = 40-100%)
	Woodlands	Others forests (Coniferous and broadleaf)	Coniferous forests	Dense and open forests of coniferous (tree layer > 2m = 25-100%; shrub and herbaceous layer < 2m = 0-100%)	Coniferous forests	Dense and open forests of coniferous (tree layer > 2m = 40-100%)
			Beech forests	Dense and open forests of *Fagus silvatica* (tree layer > 2m = 25-100%; shrub and herbaceous layer < 2m = 0-100%)	Beech forests	Dense and open forests of *Fagus silvatica* (tree layer > 2m = 40-100%)
			Mixed forests	Dense and open mixed forests of coniferous and undifferentiated broadleaf (tree layer > 2m = 25-100%; shrub and herbaceous layer < 2m = 0-100%)	Mixed forests	Dense and open mixed forests of coniferous and undifferentiated broadleaf (tree layer > 2m = 40-100%)
			Riparian forests	Dense and open riparian forests (tree layer > 2m = 25-100%; shrub and herbaceous layer < 2m = 0-100%)		
					Undifferentiated broadleaf forests	Dense and open undifferentiated broadleaf forests (tree layer > 2m = 40-100%)
			Other broadleaf forests	Dense and open forests of others broadleaf (tree layer > 2m = 25-100%; shrub and herbaceous layer < 2m = 0-100%)	Other broadleaf forests	Dense and open forests of others broadleaf (tree layer > 2m = 40-100%)
Shrublands/ grasslands	Shrublands/ grasslands	Shrublands and grasslands	Shrublands	Shrublands (tree layer > 2m = 0-25%; shrub layer < 2m = 0-100%; herbaceous layer = 0-25%)	Shrublands	Shrublands (tree layer > 2m = 0-40%)
			Mixed shrublands/ grasslands	Mixed shrublands/ grasslands (shrub and herbaceous layer < 2m = 25-100%)	Mixed shrubland/ grasslands	Mixed shrublands/grasslands
			Grasslands	Grasslands (shrub layer < 2m = 0-25%; herbaceous layer = 25-100%)	Grasslands	Grasslands
			Bare soils	Bare soils, rocks, beach	Bare soils	Bare soils, rocks, beach
Cultivated areas	Olive trees	Cultivated olive trees	Cultivated areas	Orchards, vineyards, herbaceous cultures, and cultivated olive trees	Cultivated areas	Orchards, vineyards, herbaceous cultures, and cultivated olive trees
	Cultivated areas	Crop cultivations				
	Vineyards	Vineyards				
Urban areas	Urban areas	Urban areas	Urban areas	Urban areas, Outer-urban areas, gardens	Urban areas	Urban areas, Outer-urban areas, gardens

surface area covered by bare soils, cultivated areas, and urban areas. The vegetation types were aggregated into the four generic land-cover types for analysis (Table 2). The maps were converted to a 100 m resolution raster format in a GIS database.

Land-cover analysis

Temporal analyses were performed for the San Petrone massif and the Vico-Evisa region between 1774 and 1975 and between 1975 and 2000 using transition matrices in IDRISI® software. The transition matrices were obtained by cross-tabulating the maps pixel by pixel. The cells above the diagonal represented areas that had reached a more advanced successional stage, whereas cells below the diagonal represented regression to an earlier successional stage.

Changes occurring between the earliest, 1774, and most recent, 2000, years were characterized and evaluated by generic land-cover type and selected indices typically applied in landscape ecology. The items selected for the legend, after the evaluation to synthesize the main dynamics, were the following: no expansion and regression; forestation, i.e., shrublands/grasslands, cultivated areas, and urban areas replaced with forest; shrubland expansion, i.e., forests, cultivated areas, and urban areas replaced with shrublands/grasslands; and anthropization, i.e., forests and shrublands/grasslands replaced with cultivated areas or forests, shrublands/grasslands and cultivated areas replaced with urban areas. Maps charting these territory-scale dynamics were produced to enhance the understanding of the changes and their location in the studied areas.

Human population history

The human population history between the end of the 16th century and present day was assessed for every single municipality or village using the number of inhabitants by municipality, 72 municipalities in the San Petrone massif and 22 municipalities in the Vico-Evisa region. The population data used were as follows: (1) the review published by Casta (1993) for 1770 and 1787; (2) http://cassini.ehess.fr/cassini/fr/html/6_index.htm for 1800 to 1954, at a frequency of about once every five years; and (3) French national statistics and economic studies agency (INSEE) data for 1962 to 1999, at a frequency of about once every seven to nine years.

Number of inhabitants per municipality versus time provided a proxy indicator for reconstructing agricultural history and land-use change. We linked this database with the spatial coverage exclusively concerning urban areas in the land-cover maps for the two study areas. This was performed to follow the evolution of inhabitant density, number of inhabitants per hectare in urban areas, at three time points, 1770, 1975, and 1999, corresponding to the available data on human populations in the years closest to the land-use change analysis.

RESULTS

Changes in land-cover and landscape dynamics

San Petrone massif

Forests were the predominant land-cover type, but they decreased from 1774 to 1913 and then increased from 1913 to 2000 (Fig. 2A). In 1774, these forests corresponded to chestnut forests, 39.2%, and woodlands, 8.3% (Figs. 3A, 4). Chestnut forests were clustered around villages and particularly at elevations of 700 m, while woodlands were situated in the center of the massif at higher elevations (> 900 m). In 1975, forest had expanded to 57.8% (Figs. 2A, 3A). This progression was mostly caused by an expansion of other broadleaf forests, 16.8% (Fig. 4). The chestnut forests decreased to 39.2% in 1774 and 31.9% in 1975, and transition matrices showed a regression of chestnut forests to shrublands and a transformation of chestnut forests to other broadleaf forests in 1975 (Fig. 4). In 2000, forests had increased to occupy 65.0% of the massif (Figs. 2A, 3A). The undifferentiated broadleaf forests are problematic for following the area of land-cover types. According to Inventaire Forestier National (2006), undifferentiated broadleaf forests included 40% chestnut forests and 60% other broadleaf forests on the massif. Extrapolating from this information, we calculated the area of chestnut forest in 2000 to be 20.6%, which showed regression of chestnut forests to shrublands and

Fig. 2. Percentage cover of forests, shrublands/grasslands, cultivated, and urban areas in the San Petrone massif (a) and the Vico-Evisa region (b) from 1774 to 2000, according to the initial Plan Terrier map (1774), fiscal surveys (1913), and recent land-cover maps (1975 and 2000).
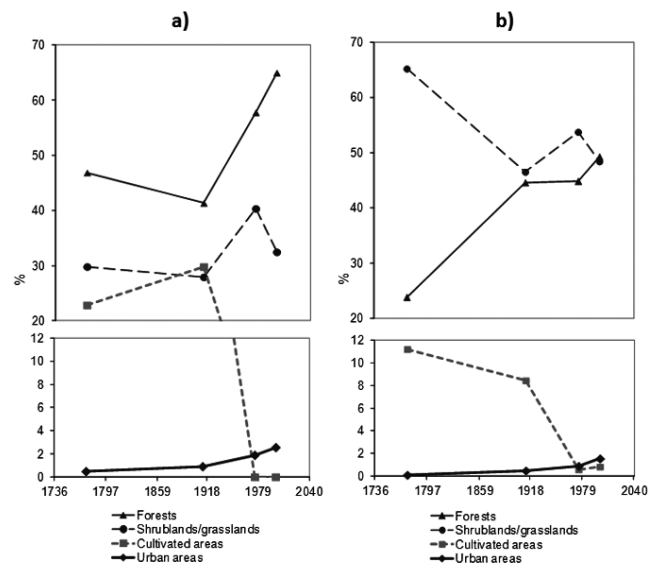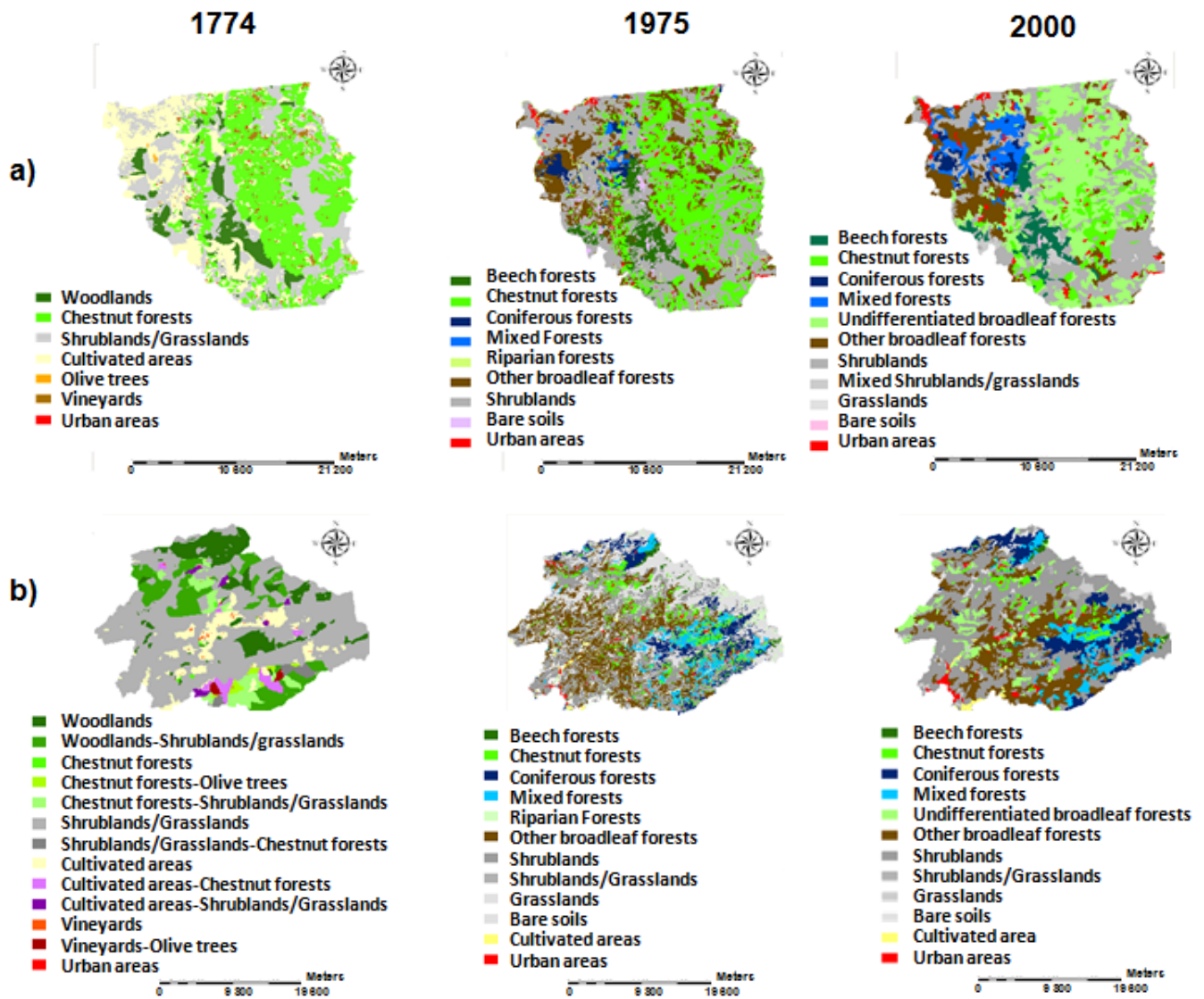
Fig. 3. Land-cover maps of the San Petrone massif (a) and the Vico-Evisa region (b) in 1774, 1975, and 2000.

the transformation of chestnut forests to broadleaf forests (Fig. 4). The other broadleaf forests covered an area of 31.1% in 2000, which showed progression of *Quercus ilex* on the massif between 1975 and 2000 (Fig. 4). An increase of mixed forests between 1975 and 2000, from 1.0% to 4.8%, and, notably, the progression of *Pinus pinaster* was observed according to the in situ field observations.

Shrublands/grasslands cover remained stable up to the 19th century, and then increased before decreasing at the end of the 20th century (Fig. 2A). Although shrublands/grasslands showed little net variation, transition matrices revealed a slight progression of shrublands/grasslands to forest, 13.3% for 1774-1975 and 14.1% for 1975-2000, especially other

broadleaf forest, that was counterbalanced by a regression of chestnut forests to shrublands (Fig. 4).

Cultivated areas covered 21.9% of the region in 1774 and 29.8% in 1913 (Fig. 2A). After 1913, these activities went into decline, and had ultimately ceased in 1975 and 2000. Transition matrices on the 1774-1975 period showed that cultivated areas had progressed to shrublands/grasslands, 13.0%, and to forests, 8.2% (Fig. 4). Urban areas increased slightly over the study period, 0.4 to 2.7% (Fig. 4).

Between 1774 and 2000, forestation increased by 27.7% (Fig. 5A). This increase was characterized by a transformation of shrublands/grasslands and cultivated areas to forests (Fig. 5A). Shrublands also expanded to an estimated 18.4% of total area,

Fig. 4. Transition matrices between 1774–1975 and 1975–2000 performed on all the land-cover types for the San Petrone massif. Totals are given for each year and each type as % of the landscape surface. Bold numbers indicate the maximum relationship between the two maps. Vertical and underlined values correspond to the sum of transition rates within the delimited transition submatrix between the different generic land-cover types.

1975 \ 1774	Woodlands	Chestnut forests	Shrublands/grasslands	Cultivated areas	Olive trees	Vineyards	Urban areas	Total
Beech forests	**3.2**	0.2	1.0	0.6				5.0
Chestnut forests	0.7	**23.9**	5.0	1.8		0.3	0.1	31.9
Coniferous forests	0.6	0.4	0.8	0.4				2.1
Mixed Forests	0.1	0.5	0.2	0.2				1.0
Riparian forests		0.4	0.4	0.4				1.2
Other broadleaf forests	1.7	4.9	5.7	3.7	0.2	0.6		16.8
Shrublands	1.7	8.3	**15.7**	**12.2**	0.1	0.5	0.1	38.5
Bare soils	0.3	0.1	0.7	0.2				1.4
Urban areas		0.6	0.3	0.7		0.1	**0.2**	1.9
Total	8.3	39.2	29.9	20.2	0.2	1.5	0.4	100.0

Underlined submatrix sums: 13.3, 8.2, 10.4, 13.0

2000 \ 1975	Beech forests	Chestnut forests	Coniferous forests	Mixed forests	Riparian forests	Other broadleaf forests	Shrublands	Bare soils	Urban areas	Total
Beech forests	**4.1**	0.1		0.1		0.2	0.7	0.2		5.4
Chestnut forests		6.9				0.4	0.8		0.1	8.2
Coniferous forests		0.1	**1.0**	0.1		0.3	0.6			2.1
Mixed forests		0.9	0.7	**0.2**	0.1	1.5	1.6			4.9
Undifferentiated broadleaf forests	0.7	**18.3**			0.2	6.0	5.5	0.2	0.2	31.1
Other broadleaf forests		1.1	0.1	0.2	**0.4**	**6.1**	4.3	0.2	0.1	12.4
Shrublands	0.2	4.3	0.3		0.4	2.1	**22.4**	**0.6**	0.4	30.7
Mixed Shrublands/grasslands	0.1			0.1			1.3	0.1		1.5
Grasslands				0.1			0.1			0.2
Bare soils				0.1			0.1	0.2		0.5
Urban areas		0.2		0.1	0.1	0.1	1.1		**1.1**	2.7
Total	5.0	31.9	2.1	1.0	1.2	16.8	38.5	1.4	1.9	100.0

Underlined submatrix sums: 14.1, 2.7

of which 9.4% resulted from forest regression. Anthropization was low and localized to areas near major roads. The majority, 51.7%, of the territory remained unaffected by changes in generic land-cover types.

Vico-Evisa region
Forests experienced a major progression from 1774 to 2000 (Fig. 2B). In 1774, these forests corresponded to heterogeneous land-cover types (Figs. 3B, 6). Woodlands were represented by *Quercus ilex* at low and midrange elevations and by *Pinus* sp. and *Fagus sylvatica* at high elevations. Chestnut forests covered small areas that could not be precisely calculated with the given information. By 1975, forest had progressed to cover 44.8% of the region (Figs. 2B, 3B). This progression was mostly caused by an expansion of other broadleaf forests, 20.4% (Fig. 6). Nevertheless,

transition matrices on the 1774-1975 period revealed a regression of forests to shrublands and bare soil, 16.2% (Fig. 6). As in the San Petrone massif, chestnut forests regressed into shrublands and were replaced by other broadleaf forests. In 2000, forest had increased to 49.2% of the region (Figs. 2B, 3B). This progression corresponded to an increase of (1) *Quercus ilex* areas in other broadleaf forests, 20.4% in 1975 and 26.2% in 2000, and (2) *Pinus pinaster*, 8.1% in 1975 and 10.5% in 2000 for coniferous forests, 5.9% in 1975 and 6.3% in 2000 for mixed forests (Fig. 6). Nevertheless, transition matrices on the 1975-2000 period revealed a regression of forests either to shrublands/grasslands, 9.3%, or to other broadleaf forests, 5.5% (Fig. 6).

Shrublands/grasslands dominated the region (Fig. 2B). Shrublands/grasslands cover decreased in the 19th century,

Fig. 5. Maps of landscape dynamics between 1774 and 2000 for the San Petrone massif (a) and the Vico-Evisa region (b).
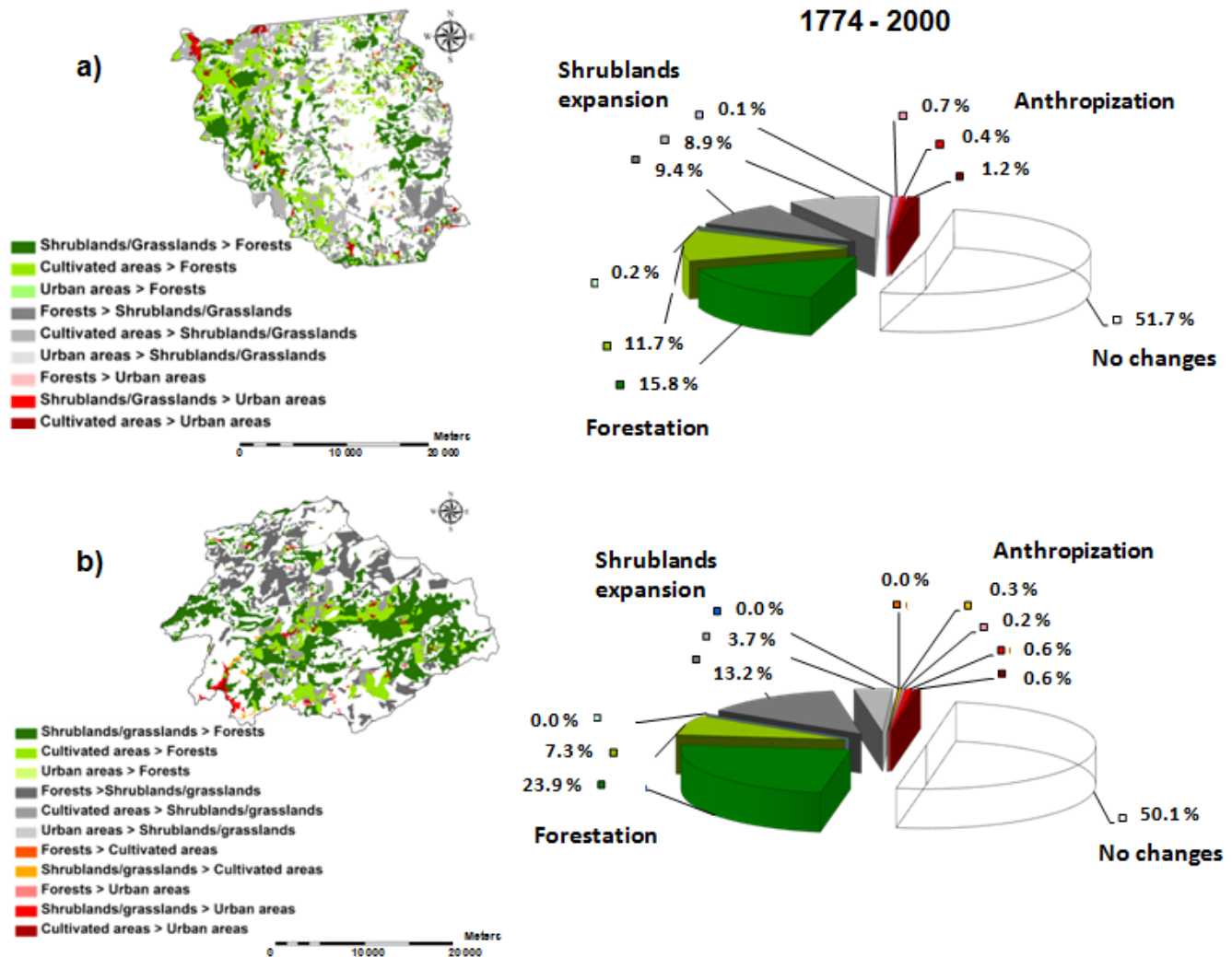
and then increased before decreasing again toward the end of the 20th century (Fig. 2B). Transition matrices showed a major progression of shrublands/grasslands to forests, 23.5% for 1774-1975 and 14.7% for 1975-2000, notably to other broadleaf forests (Fig. 6).

Cultivated areas covered 11.2% of the region in 1774 and 8.4% in 1913 (Fig. 2B). After 1913, these activities went into strong decline, down to just 0.6% of the region's land in 1975 and 0.8% in 2000. Transition matrices on the 1774-1975 period showed a progression of the cultivated areas to shrublands/grasslands, 13.0%, and forests, 6.3% (Fig. 6). Urban areas remained small in the region, but increased over the study period from 0.1% in 1774 to 1.5% in 2000 (Fig. 6).

Between 1774 and 2000, the expansion of forested lands occurred throughout the region (Fig. 5B), reaching an estimated 31.3%, typically driven by a progression of shrublands/grasslands to forests, 23.9% (Fig. 5B). Shrublands increased to 16.9%, of which 13.2% resulted from forest regression. Anthropization was low in the region and remained localized to the coastal areas (Fig. 5B). A small majority, 50.1% of the territory, remained unaffected by changes in the generic land-cover types.

Human population changes
The human population of the San Petrone massif reached its peak in 1856 at 29,606 inhabitants, i.e., 62.7 inhabitants/km², in the 72 municipalities (Fig. 7). The human population of the Vico-Evisa region was generally lower and reached its peak in 1891 at 15,779 inhabitants, i.e., 25.3 inhabitants/km², in 22 the municipalities (Fig. 7). In both the study areas, the human population rose from the 18th century to the end of the 19th century, particularly in the Vico-Evisa region where the

Fig. 6. Transition matrices between 1774–1975 and 1975–2000 performed on all the land-cover types for the Vico-Evisa region. Totals are given for each year and each type as % of the landscape surface. Bold numbers indicate the maximum relationship between the two maps. Vertical and underlined values correspond to the sum of transition rates within the delimited transition submatrix between the different generic land-cover types.

1975 \ 1774	Woodlands	Woodlands-Shrublands/grasslands	Chestnut forests	Chestnut forests-Olive trees	Chestnut forests-Shrublands/Grasslands	Shrublands/Grasslands	Shrublands/Grasslands-Chestnut forests	Cultivated areas	Cultivated areas-Chestnut forests	Cultivated areas-Shrublands/Grasslands	Vineyards	Vineyards-Olive trees	Urban areas	Total
Beech forests	0.6	0.1				0.1								0.8
Chestnut forests	0.4	0.7	0.2	0.1	0.9	3.2	0.1	0.8	0.2	0.1				6.5
Coniferous forests	**3.6**	0.7			0.1	3.4	0.1	0.3						8.1
Mixed forests	1.2	0.7		0.2	0.2	2.8	0.2	0.5	0.1					5.9
Riparian Forests	0.1	0.2		0.1	0.2	1.8	0.1	0.5	0.1	0.1				3.1
Other broadleaf forests	0.8	2.8	0.1	0.1	1.1	11.6	0.2	2.5	0.8	0.2	0.1	0.3		20.4
Shrublands	1.5	3.9	0.1	0.3	1.9	15.3	0.4	2.8	0.9	0.3	0.2	0.2	0.1	27.7
Shrublands/Grasslands					0.1	1.1		0.3						1.5
Grasslands	1.1	0.9			0.1	3.4		0.1		0.1				5.6
Bare soils	3.2	2.8			0.3	11.5	0.2	0.4	0.1	0.1				18.6
Cultivated areas						0.3		0.2						0.5
Urban areas						0.3		0.4			0.1		0.1	0.8
Total	12.4	13.0	0.3	0.7	4.8	54.7	1.2	8.7	2.2	0.8	0.3	0.4	0.1	100.0

Submatrix sums (underlined): 23.5 ; 6.3 ; 16.2 ; 13.0

2000 \ 1975	Beech forests	Chestnut forests	Coniferous forests	Mixed forests	Riparian forests	Other broadleaf forests	Shrublands	Shrublands/Grasslands	Grasslands	Bare soils	Cultivated area	Urban areas	Total
Beech forests	**0.4**									0.1			0.4
Chestnut forests		2.6	0.1	0.2	0.1	0.4	0.5		0.1			0.1	3.9
Coniferous forests		0.4	**5.9**	0.6	0.1	0.1	1.6		0.3	1.5			10.5
Mixed forests	0.1	0.9	1.0	2.3	0.1	0.3	1.3		0.1	0.2			6.3
Undifferentiated broadleaf forests	0.2	0.5		0.2	0.4	3.1	1.3	0.1	0.1	0.4			6.2
Other broadleaf forests		0.8	0.2	2.2	1.3	10.8	5.1	0.2	0.1	1.8		0.1	22.5
Shrublands	0.1	1.4	0.8	0.5	0.9	5.5	**16.3**	0.6	4.4	12.5	0.1	0.2	43.3
Shrublands/Grasslands							0.3		0.1	0.1			0.5
Grasslands			0.1			0.1	0.6	0.2	0.3	0.2	0.2		1.6
Bare soils						0.1	0.1		0.1	1.7			1.9
Cultivated area					0.1	0.1	0.1	0.3			0.2		0.8
Urban aeras		0.1			0.1	0.1	0.5	0.2		0.1		0.6	1.5
Total	0.8	6.5	8.1	5.9	3.1	20.4	27.7	1.5	5.6	18.6	0.5	0.8	100.0

Submatrix sums (underlined): 14.7 ; 9.3 ; 0.3

population tripled (Fig. 7). Rural exodus began in the early 20th century with slow population decreases in both study areas. The rate of decline remained relatively constant until the end of the 20th century, except during the First World War, 1914-1918, when the population abruptly dropped. The population decline coincided with the cultivated areas decline and significant reforestation on the two study sites (Fig. 2). After 1990, the population slowly increased in both areas. In 1999, the population of San Petrone massif was 6110 inhabitants, i.e., 12.9 inhabitants/km², and the population of the Vico-Evisa region was 3793 inhabitants, i.e., 6.1 inhabitants/km² (Fig. 7). Over the course of the study period, there was an increase in the populations of urban areas and a shift of population densities from rural areas to areas near main roads, in the northwest, and coastal areas, in the east, of the San Petrone massif and to coastal areas, in the west, of the Vico-Evisa region (Fig. 8).

DISCUSSION AND CONCLUSION

In Corsica, long-term vegetation dynamics are directly related to population history. In 1584, the governor of Genua, modern-day Genova, ordered all Corsican farmers and landowners to plant four trees yearly, a chestnut tree, an olive tree, a fig tree, and a mulberry tree. Many communities owe their origin and former richness to the ensuing chestnut woods (Perry 1967). The sweet chestnut is a tree species that has attracted particular attention from human populations (Conedera et al. 2004). It is for these reasons that several regions of Corsica are covered by chestnut forests, notably the Castagniccia region (San Petrone massif), which at one point in time was the most populated region of Corsica (Perry 1967). In 1774, chestnut forests covered the largest fraction of wooded areas in the San Petrone massif and the lowest fraction in the Vico-Evisa region. The development of chestnut forests led to the replacement of native *Quercus ilex* forests that palynoecological analyses show had dominated the island for

Fig. 7. Number of inhabitants versus time in the San Petrone massif (a) and the Vico-Evisa region (b) over the last 230 years.
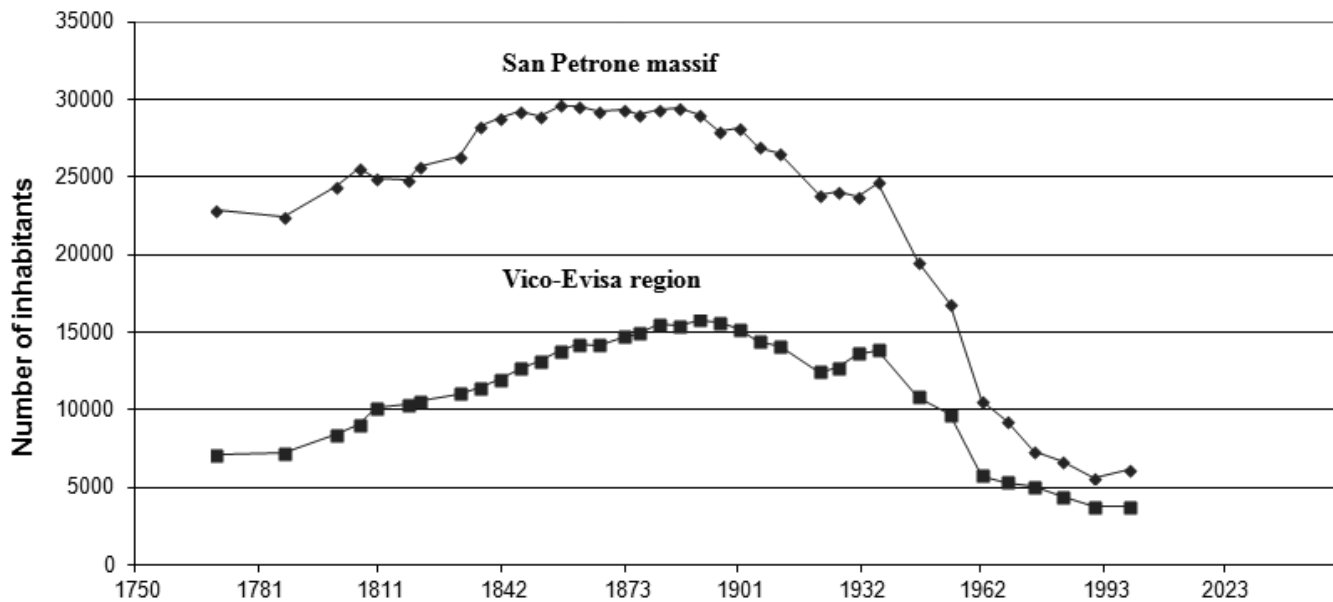

thousands of years (Reille 1992, Carcaillet et al. 1997). Against a background of industrial revolution and two world wars, the population of Corsica declined from almost 300,000 inhabitants in 1890 to 150,000 inhabitants in the 1950s, through emigration to the mainland and colonies (Lefèbvre 1957). The areas dominated by intensively tended chestnut groves became progressively abandoned because of the rural exodus and related phenomena (Pitte 1986). Other drivers of chestnut forest abandonment were ink disease (Vettraino et al. 2005) and the accidental introduction of chestnut blight around 1920, which seriously damaged chestnut tree quality and yields (Pitte 1986). Over the study period, from 1774 to 2000, in both study areas, chestnut forests either regressed into shrublands or were replaced by other broadleaf forests. The total area of the San Petrone massif occupied by chestnut forests was halved between 1774 and 2000, i.e., -0.09% yr^{-1} between 1774 and 1975 and -1.42% yr^{-1} between 1975 and 2000. In parallel, both study areas experienced a significant increase in forest cover between 1774 and 2000, during which forests replaced shrublands and cultivated areas. Between 1975 and 2000, the increase of other deciduous forests was equally strong, i.e., +3.40% yr^{-1} in the San Petrone massif and +1.14% yr^{-1} in the Vico-Evisa region. Our results also showed a significant increase in coniferous forests with +3.00% yr^{-1} in the San Petrone massif and +0.94% yr^{-1} in the Vico-Evisa region between 1975 and 2000. In southern France, in the absence of disturbances, average forest expansion was 1.06% yr^{-1} (Debussche et al. 1987), and this highlights comparatively strong forest dynamics for the San Petrone massif. Even

though both study sites experienced high levels of forestation, we also observed a regression of forests to shrublands in both study areas. These results could be linked to the occurrence of wildfires in the Mediterranean region (Vález 2000).

The San Petrone massif and the Vico-Evisa region could be considered social-ecological systems. Folke et al. (2010) defines the dynamics and development of complex social-ecological systems through three aspects: resilience, adaptability, and transformability. The system is said to have undergone a regime shift (Scheffer et al. 2001) that may be reversible, irreversible, or effectively irreversible, i.e., not reversible on time scales of interest to society. Our study, on long time scales, illustrated the drastic transformation of *Quercus ilex* forests for the development of agriculture and the cultivation of chestnut and a feedback to mostly *Quercus ilex* forests following subsequent land abandonment. These results reflect the resilience and high adjustment of the system, even after a regime shift, as notably observed in the San Petrone massif. In the absence of management, chestnut forests tended to be invaded by other tree species, giving way to an evolutionary dynamic toward climax forests, as observed in many European regions in recent decades (Arnaud et al. 1997, Conedera et al. 2000, 2001). However, the strong progressions of broadleaf forests also concern coniferous forests that might have been dependent on rapid colonization, notably through the abandonment of open-land habitats (Quézel and Médail 2003), because the recruitment rate for pines is also associated with declines in local human

Fig. 8. Maps of population density (number of inhabitants per hectare of urban areas) in 1770, 1975, and 1999 for the San Petrone massif (a) and the Vico-Evisa region (b).
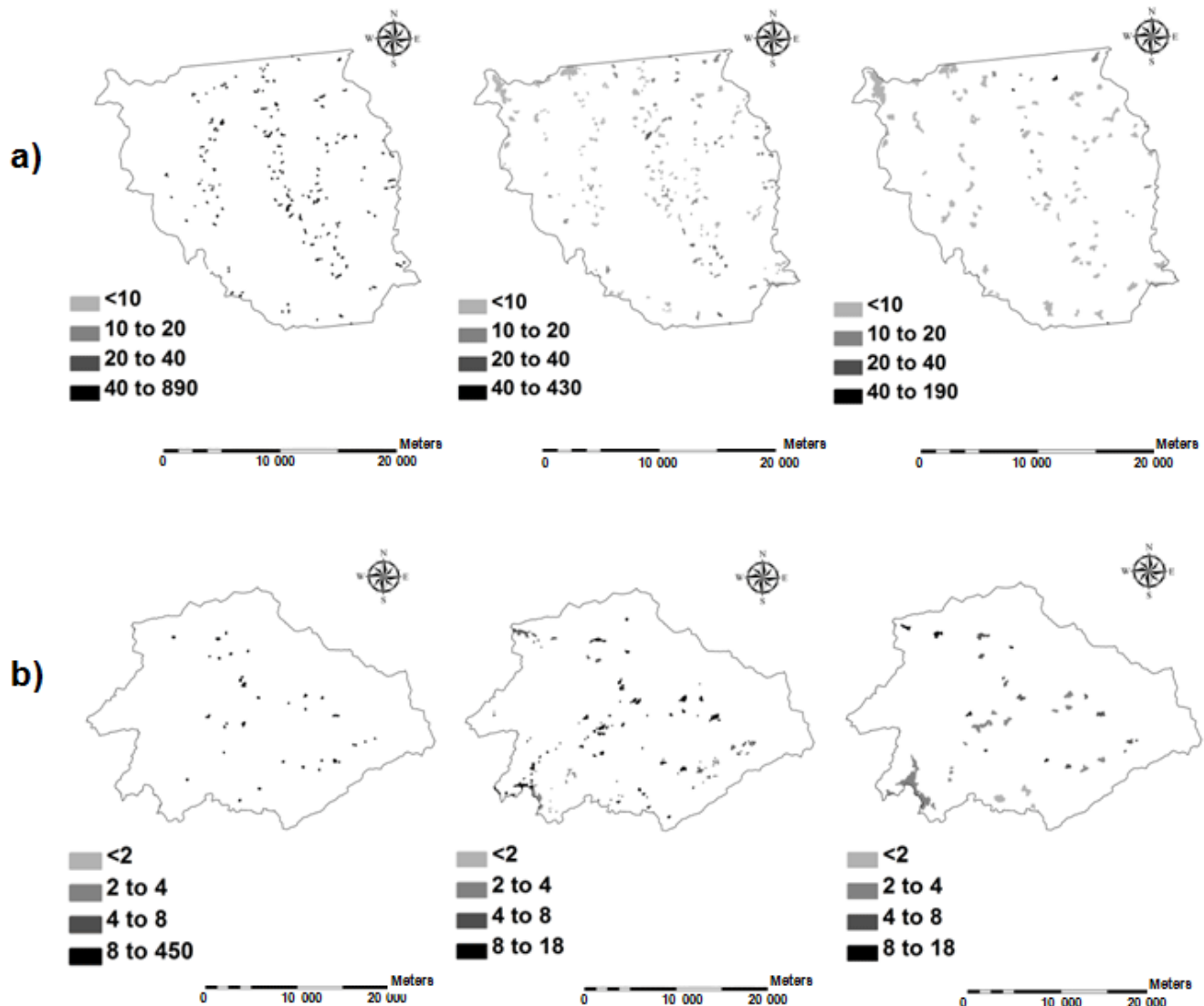
population and regional livestock (Curt et al. 2003, Chauchard et al. 2007). The dynamics of a system at a particular scale-of-interest cannot be understood without taking into account the dynamics and cross-scale influences of the processes from scales above and below it. For example, dynamics include disturbances such as forest pest outbreaks or forest fires. Work on resilience suggests that many of the observed shifts, crises, or nonlinearities observed in ecological systems are from processes and structures interacting across scales (Walker and Meyers 2004). Because social-ecological systems are dominated by human action, their adaptability is mainly a function of management. Our study illustrated that the social-ecosystems studied may be effectively reversible according to

management. Indeed, without constant care, chestnut trees are heavily prone to damage and disease; they slowly decay and stop producing quality fruits, as exemplified by the collapse of most of Corsica's chestnut forests over the 20th century (Michon 2011). However, around 1980, local initiatives started to re-establish the chestnut economy with a compromise between traditions tied to chestnut culture and the modernity of a market economy (Auclair and Michon 2009). Analysis of long-term variability, such as changes in the frequency of events, can provide important insights into how human activity has modified the probability of extreme events and threshold transgressions.

The alternating regimes of social-ecological systems can have significantly different implications for society, and so, from a purely human point of view, may be considered desirable or undesirable. This desirability can be expressed in economic terms, social terms, or ecological terms (Scheffer et al. 2000). The concept of ecosystem services was used by the Millennium Ecosystem Assessment to link ecological processes to human well-being (Carpenter et al. 2009). In line with the Economics of Ecosystems and Biodiversity definition (Balmford et al. 2008), we use "ecosystem service benefits" to mean the end products that are directly used by humans. Here, human action through massive chestnut introduction in the 16th century has completely modified the ecosystem to build a social-ecological system with very specific service benefits such as the production of food and animal fodder. This ecosystem change helped develop and retain human populations in these areas. The population decline associated with abandoned chestnut trees entails a decrease in specific ecosystem service and in species richness and biodiversity, which correlates closely to a steady increase in the leaf area index of the forest canopy (Gondard et al. 2001). Regime shifts in social-ecological systems can cause rapid yet substantial changes in ecosystem services and human well-being. Regime shifts may be exacerbated by human action or equally by the absence of human action, as was found here. Attempts to optimize a single service often lead to reductions or losses of other services. For example, forested areas provide a variety of extractive and nonextractive goods and services (Rose and Chapman 2003), and a region managed for mining may lose its value for carbon sequestration, flood control, or wilderness and biodiversity protection. In our context, effective decision making, enabling policy makers to gain a comprehensive view of the ecosystem service trade-offs involved, should address the cumulative and synergistic effects of their decisions.

In summary, almost all the landscape changes that have occurred in the study areas were because of changing human influences. The abandonment of farming activities and the accompanying sharp decrease in resident populations has clearly favored natural ecological succession and the degradation of the agricultural landscape. Replacement was essentially marked by *Quercus ilex* forests, which formed the original forests before human impact, and by the introduction of *Pinus pinaster*. Corsica currently has relatively low population densities, with only small resident communities, little mechanized agriculture, and poor communications infrastructures (Pitte 1982). In addition, features that attract tourists, such as activities tied to attractive mountain landscapes, are still underdeveloped. However, chestnut producers are striving to revive the chestnut economy, as part of a local reappropriation movement that champions rurality, insularity, and cultural identity as positive values founding local development. Even if it is still in search of sustainability, the 21st century chestnut economy is experiencing a revival

through denaturalization of the ecosystem and socio-technical modernization (Michon 2011). In this context, regional land planning, forest management, and restoration are still limited on Corsica. Our study highlights the value of small-scale approaches for understanding the ecological consequences of land-use abandonment and present and future land-management decisions. Because this kind of study needs to be integrated and transferred to landscape and forest managers and decision makers, it is important to develop user-friendly decision support tools (Scarascia-Mugnozza et al. 2000).

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