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Contemporary land use changes in prealpine Mediterranean mountains: a multivariate GIS-based approach applied to two municipalities in the Southern French Prealps

Fabrice Taillefumier*, Hervé Piégay

UMR 5600-CNRS Environnement-Ville-Société, 18, rue Chevreul, 69362 Lyon cedex 07, France
Laboratoire Rhodanien de Géographie de l'Environnement, Université Lumière Lyon 2, 5, avenue Pierre Mendès-France, 69676, Bron cedex, France

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Abstract

This paper examines recent land use changes in the Mediterranean mountain setting of the Diois region of the Southern French Prealps, which has undergone considerable change related to evolution of the agro–sylvo–pastoral system and the decline of agriculture since the beginning of the 19th century. The aim was to describe the evolution of land use and the influence of environmental factors on it. Land use maps were created for 1828, 1956 and 1991 to quantify landscape modifications. Changes in anthropogenic pressure on land were assessed from changes in population and livestock. Relationships between several environmental factors (e.g. bedrock classes, surface deposits, elevation, slope, aspect, dip, dip orientation and relation between dip and slope) and land use changes were appraised. Social, economic and technical changes have influenced the agricultural system. Between-class Multiple Correspondence Analysis (MCA) showed that decision-making during two periods, 1828–1956 and 1956–1991, was influenced by environmental variables, notably slope, but also elevation, bedrock type and surface deposits. Impacts on hillslopes, fluvial processes and the landscape in general resulting from land use change have created specific problems for land management and development.

Keywords: Land use changes; Agricultural revolution; Multivariate statistical analysis; GIS; Mountain landscape

* Corresponding author.
E-mail addresses: fabrice.taillefumier@wanadoo.fr (F. Taillefumier), piegay@sunlyon3.univ-lyon3.fr (H. Piégay).

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1. Introduction

For several centuries, many mountainous regions of Western Europe such as the Massif Central, the Alps, the Pyrenees and the Apennines have been subject to considerable anthropogenic pressure (Beeching and Brochier, 1989; Vallauri et al., 1997; d'Angelo et al., 2000). The traditional agro–sylvo–pastoral systems of these areas intensified during the 19th century because of increased population density and the agricultural and industrial revolutions. Following a period of overpopulation, these mountain areas have since undergone agricultural decline and major changes in agricultural practices and land use (Blanchard, 1945; Meyzenq, 1984; Arnáez-Vadillo et al., 1990; Molinillo et al., 1997). The extension of shrub and forest communities into previously agricultural and pastoral areas is the main modification observed (Barbéro and Quézel, 1990; Chédin, 1990; Brossard et al., 1993; Guidi and Piussi, 1993; Bommel and Lardon, 2000). This pattern has two significant environmental and societal consequences:

1. Human perception and landscape management. Older landscapes are often of particular interest because of their heritage and attractiveness (Brossard and Wieber, 1984; Fischesser, 1991; Brossard et al., 1993, 1996; Josselin et al., 1995). Landscape has thus become a consumer product by taking on heritage value. The closing (i.e. reduction in panoramas) and simplification of landscapes can therefore be perceived in contrasting ways by users and decision-makers, possibly leading to conflicts between local and external interests.
2. Hillslope dynamics and channel changes (Bravard and Peiry, 1993; Billi and Rinaldi, 1997; Garcia-Ruiz et al., 1997; Liébault and Taillefumier, 2000). The spontaneous afforestation of mountain areas has been interpreted as a process that increases hillslope stability, thereby explaining a reduction in sediment supply to river systems. This can lead to riverbed narrowing, degradation and sometimes paving downstream (Liébault and Piégay, 2001), in turn undermining infrastructures and lowering water tables. To counter this trend, the possibility of restoring sediment supply from hillslopes has been suggested for the Drôme and the Eygues basins (Landon et al., 1998; Bravard et al., 1999; Liébault et al., 2001).

Land use change has been approached at various scales. Relying primarily on data of communes (i.e. municipalities), several small-scale studies (from 100 to several thousand km^2) have identified land use change within catchments and regions. At this scale, focus is often on the links between land use change and synchronous changes of other environmental factors such as river geometry and sediment transport (Piégay, 1995; Landon, 1999; Liébault and Taillefumier, 2000). In these cases, environmental change is interpreted as resulting from several causes, land use change being only one of them. However, it can be difficult to isolate the causes of change and order of them according to their respective importance. In other approaches, measurements made on experimental plots of only a few square metres relate specific degradation to land use types, establishing physically based links between land use change and environmental change. However, it is usually difficult to extrapolate local observations to wider areas and longer time scales (Bernard-Allée and Cosandey, 1991; Lasanta et al., 2000), although recent results from the MEDALUS project have made major advances in this direction (Kirkby et al., 1998).

Studies conducted at an intermediate scale through the use of land survey maps or aerial photographs are more rare. Examples of such studies in the Central Alps (Tappeiner et al., 1998), Sardinia (d'Angelo et al., 2000) and the Spanish Pyrenees (Arnáez-Vadillo et al., 1990) argue that, at this scale, environmental factors control both the spatial organization of and changes in land use. This kind of research complements results found at both larger and smaller scales because it highlights the environmental controls that affect land use, rather than the environmental consequences of varying land use. This approach may clarify why land use change observed in a given catchment may have variable environmental consequences downstream, depending upon the environment in which it occurs.

In the last few decades, regardless of the spatial scale, studies of land use change have emphasized the role of human factors while downplaying environmental controls (Josselin, 1995; Josselin et al., 1995), but more research is needed to determine the relative importance of human and natural controls on land use change. With this in mind, the aim of this study is twofold: (i) to identify contemporary change in land use for three specific dates using the Napoleonic land survey, aerial photographs and statistics on population density and livestock; (ii) to explain the geographical complexity of these changes by relating them to environmental variables that reflect possible factors controlling land use (Callot, 1978; Arnáez-Vadillo et al., 1990; Darracq, 1992; Del Barrio et al., 1997). We used GIS to process information layers and extract data for statistical analysis, so as to test hypotheses and establish links between changes in land use and the environmental factors that may control them.

2. Study area

The study was conducted in the surroundings of Bourdeaux, in the Upper Roubion catchment (Fig. 1a). This region is situated at the border of the Diois mountains, in the Drôme department, in the Southern French Prealps. Following preliminary small-scale studies of the Diois and Baronnies regions (Liébault and Taillefumier, 2000), two rural municipalities found to be representative of the evolution observed within these two regions were selected as study sites. The communes of Bézaudun and les Tonils cover about 31 km^2 within this large area (Fig. 1b).

The climate is sub-Mediterranean, with a mean annual temperature of 11 °C and mean annual precipitation of about 900 mm (meteorological station of Bourdeaux). Elevation ranges from 450 to 1550 m and steep slopes are common. The lithology is quite heterogeneous but is dominated by marl and limestone facies. Different types of surface deposits partially cover the bedrock. Thus, the climate, lithology and topography of the area form an environment relatively sensitive to anthropogenic pressures.

The two communes correspond to two subbasins of the Roubion River, drained by the Bine and Soubrion Creeks. Liébault and Piégay (2001) observed marked decreases in active channel width for both stream channels between 1956 and 1991, but fluvial changes were greater on Bine Creek than those observed on the Soubrion, leading to the hypothesis

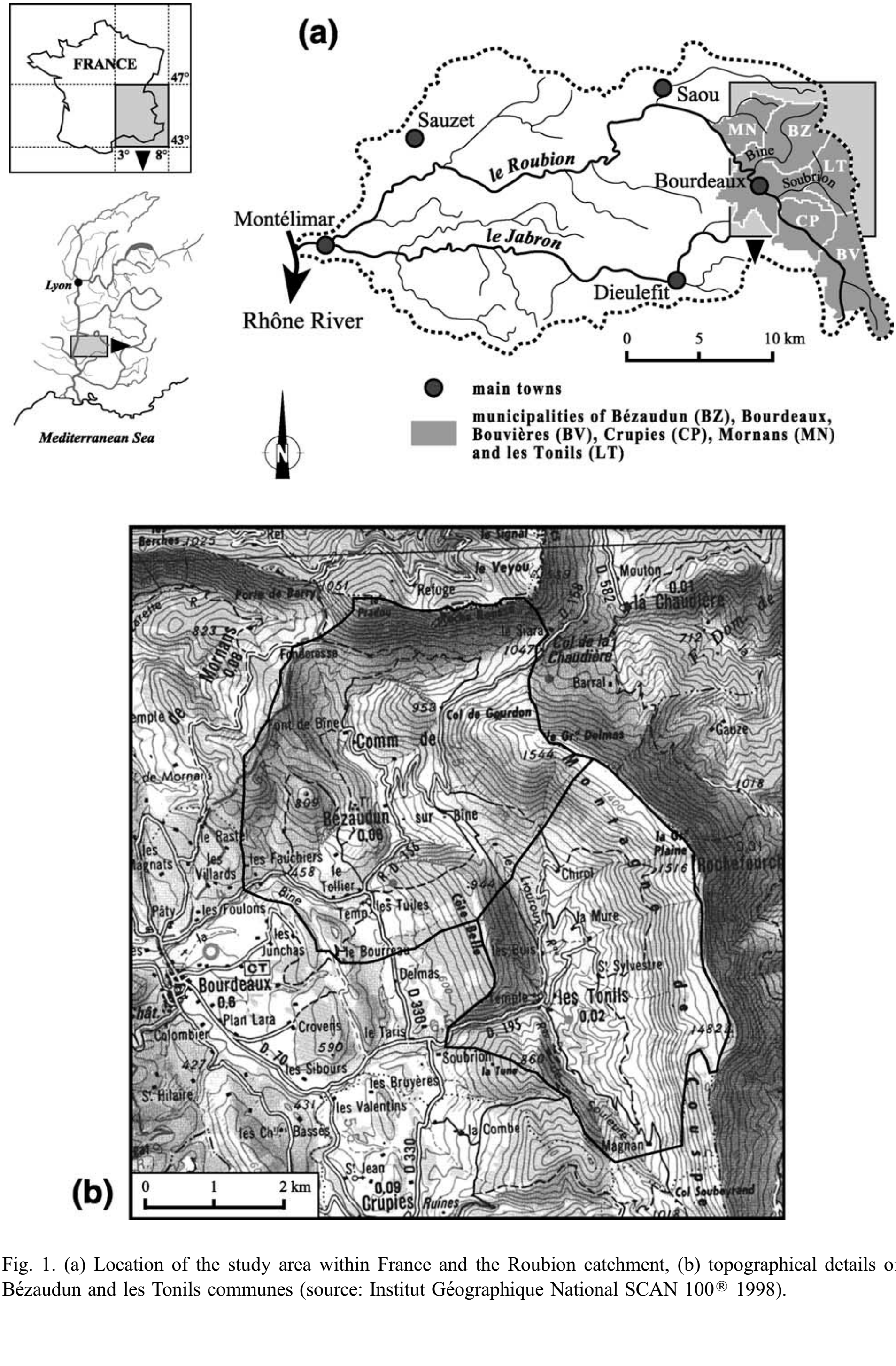


Fig. 1. (a) Location of the study area within France and the Roubion catchment, (b) topographical details of Bézaudun and les Tonils communes (source: Institut Géographique National SCAN 100® 1998).

that changes in vegetation cover may have contrasting impacts on sediment supply to the channels.

3. Materials and methods

3.1. Assessment of changes in anthropogenic pressure on land

3.1.1. Archives of human and livestock densities

Statistics on population and livestock densities can be used to examine anthropogenic pressure on the environment. We examined archives at the level of both communes and the Drôme department. Population censuses have been conducted regularly since the end of the 18th century at intervals of 5–10 years. We also examined the composition and population of livestock from 11 surveys and statistics produced between 1789 and 1988. Surveys and economic statistics, as well as reports, notes and correspondences, were also used to understand how rural society functioned in the two communes, as well as those of the neighboring communes. In particular, the 1860 survey, composed of 100 questions, provided a complete assessment of the economy and rural life in the mid-19th century.

3.1.2. Changes in land cover

Contemporary change in land use was studied from three maps made in 1828, 1956 and 1991. The Napoleonic land survey allows us to reconstruct land use mosaics at the beginning of the 19th century. This document is composed of two parts: (i) a large-scale map (1:2500–1:5000) showing fields; (ii) a data sheet for each field, with information about land use, surface area, income and landowners. These documents were prepared when the population of the region was densest. We had to interpret the meanings of land use terms used in this survey in order to compare them with terms in the more recent ones. For 1956 and 1991, we used aerial photographs for land use mapping. These were rectified, geo-referenced and mosaicked (GeoImage® software) before being used to identify land use types. On all of the maps, five main land use types were defined for comparison: ploughed land, pasture and meadow, shrub cover, forest and other (orchards, vineyards, housing and bare soil). Land cover maps were digitized and transferred into a GIS with ArcInfo® software. Land cover changes for the periods 1828–1956 and 1956–1991 were calculated by overlaying the three maps.

3.2. Environmental variables

3.2.1. Data collection

We selected eight environmental variables (bedrock lithology, type of subsurface deposit, dip of bedrock, orientation of bedrock dip, elevation, slope, slope aspect and relationship between dip and slope) considered as possible influences upon the spatial distribution of land use types in rural communities (Table 1). Bedrock lithology was derived from available 1:50,000 and 1:20,000 geological maps (Van Romphey, 1959; Cuche, 1960; Flandrin, 1970) and complementary field surveys. A limited number of synthetic classes were defined based on the kind and proportions of the main mineralogical

Table 1
Definitions of the eight environmental variables used in the between-class MCA for the periods 1828–1956 and 1956–1991; the numbers (from 1 to 64) correspond to those used in Figs. 5a and 6a; the percentages are for the distribution of pixels (entire population) according to the classes of the environmental variables

No.	Bedrock classes	Percent (%)	No.	Surface deposits classes	Percent (%)	No.	Dip classes (°)	Percent (%)	No.	Dip orientation classes	Percent (%)
1	Massive limestones	20.6	8	Bare rock outcrops	62.9	13	0–9	1.2	21	N	7.4
2	Massive siliceous limestones + bedded siliceous limestones	3.7	9	Weathering mantle derived from calcareous sandstones + colluvium derived from calcareous sandstones + weathering mantle and colluvium derived from marls (Albin and Gargasin) + weathering mantle and colluvium derived from marls (Valanginin)	7.0	14	10–19	16	22	NE	1.1
3	Calcareous sandstones	3.2	10	Talluvium on marly limestones	1.8	15	20–29	30.9	23	E	2.5
4	Bedded limestones	15.6	11	Talluvium + stratified slope deposits or glacis	12.9	16	30–39	17.3	24	SE	2.3
5	Interbedded limestone and marl	31.5	12	Screes or stratified talluvium or debris cones + screes or stratified talluvium	13.7	17	40–49	16.1	25	S	5.0
6	Marl interbedded with limestone	15.3	12a	Glacis (Turonian slopes)	1.7	18	50–59	6.0	26	SW	43.6
7	Marls	10.2				19	60–69	2.7	27	W	35.8
						20	70–90	9.8	28	NW	2.4

No.	Elevation classes (m)	Percent (%)	No.	Slope classes (°)	Percent (%)	No.	Aspect classes	Percent (%)	No.	Relationship between dip and slope classes	Percent (%)
29	400–499	2.4	40	0–5	0.1	49	N	4.8	57	Dip exactly matching slope gradient	8.6
30	500–599	11.9	41	6–8	0.4	50	NE	4.9	58	Dip a little less than slope gradient	2.4
31	600–699	17.7	42	9–12	0.4	51	E	7.5	59	Dip a little exceeding slope gradient	22.5
32	700–799	17.9	43	13–16	2.2	52	SE	5.6	60	Other dips conform to slope gradient	27.4
33	800–899	14.9	44	17–20	5.8	53	S	17.8	61	Dip opposite and approximately perpendicular to slope gradient	2.8
34	900–999	9.7	45	21–25	2.3	54	SW	29.3	62	Dip opposite (acute or obtuse angle) to slope gradient	10.6
35	1000–1099	7.0	46	26–30	5.1	55	W	22.7	63	Other opposite dips	13.9
36	1100–1199	5.1	47	31–37	2.2	56	NW	7.4	64	Other types	11.8
37	1200–1299	5.0	48	38–90	0.4						
38	1300–1399	5.0									
39	1400–1499	3.4									

and chemical elements as well as the sedimentary architecture (e.g. interbedded limestone and marl). The surface deposits (sedimentary materials between the bedrock and the soil) were mapped when their thickness exceeded 25 cm, following the field survey method detailed in Liébault et al. (1998). Samples (200) allowed us to analyse six main properties for classification. These included the matrix (texture and total content of $CaCO_3$) and the coarse elements embedded in the matrix (rock type, morphology, size and percentage of rock debris). Initially, 12 classes were mapped, but these were ultimately grouped into six classes (Table 1). Using Erdas Imagine® software, elevation, slope and aspect were extracted from a 50 m digital elevation model (DEM) from the Institut Géographique National (BD ALTI®) and then transformed into discrete classes. The DEM was made from contours of 1:50,000 topographic maps. Horizontal precision is 5–10 m; vertical precision is about 10 m but changes with relief (lower accuracy on mountain tops and steep slopes and better accuracy in more level areas). Elevation was classified by 100-m categories, and slopes were divided into 11 classes according to thresholds in their distribution. Eight conventional classes were employed for aspect. We drew maps of dip and dip orientation using existing geological documents and complementary field surveys. For these two variables, the resulting values were divided into eight classes. An overlay of slope, aspect, dip and dip orientation covers was made to create a new variable expressing the relationship between dip and slope.

3.2.2. Environmental characteristics of the studied area

The natural conditions of the communes of Bézaudun and les Tonils are very diverse (Table 1 and Fig. 2). The bedrock lithology is quite heterogeneous, although the region is composed only of Late Jurassic and Cretaceous sedimentary rocks. Resistant facies and soft facies account for 43.1% and 25.5% of the total area, respectively. The various surface deposits cover almost 40% of the area. Elevation variations (Fig. 2a) induce climatic and pluviometric gradients. Slopes are relatively steep (Fig. 2b) but some limestone escarpments were smoothed by the DEM extraction procedure. Most slopes face west, south–west or south; the other aspect classes cover only small portions of the area. Dip is more diverse; all of the possible classes are present, and although the classes between 10° and 49° are prevalent (80% of the total), the 70–90° class is also fairly common. Dip orientation is more homogeneously distributed. The variable expressing the relationship

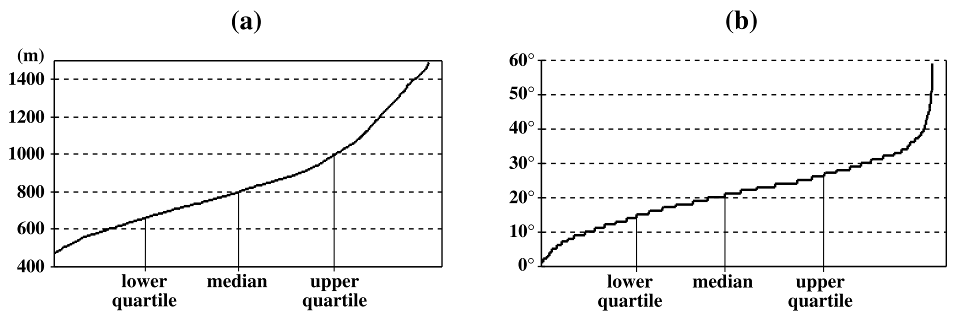


Fig. 2. Distribution of pixels (entire population) of the continuous variables: (a) elevation and (b) slope.

between dip and slope was organized in eight classes. Dips in conformity with slope gradient (Table 1: modalities 57, 58, 59 and 60) represent a little more than 60% of the total, opposite dips (Table 1: modalities 61, 62 and 63) represent 27% and the other classes represent 12%.

3.3. Statistical analysis

After the land use data and environmental variables had been transferred into a GIS, the vector thematic layers were converted into raster layers to construct the final database made of more than 12,000 pixels, each representing a surface area of 2500 m^2. To study which environmental factors controlled land use change during each period (1828–1956 and 1956–1991), we extracted a sample of 20% of the pixels from the database. The sample was stratified to maintain the relative frequency of each land use change, making it necessary to extract two different samples (one for each period) because the two distributions of land use change were different. Multivariate statistical analysis was then used to link land use types (ploughed land, pastures, shrub cover, forest cover and 'other land uses') and land use change over the two periods (1828–1956 and 1956–1991) to environmental variables such as elevation and slope (Table 1). The land use change corresponds to a new categorical variable for which the modalities are combinations of two land use types, those of the first date and those of the second date. For example, the change in land use observed during the 1828–1956 period can have various characters such as the modality '1828 Forest → 1956 Pasture', but also the modality '1828 Forest → 1956 Forest'.

Spatial autocorrelation was measured to determine the lag distance above which the values were statistically independent. Various functions were used including Moran's I (1950) and Geary's c (1954) for the continuous variables; and function J for the categorical variables (Aubry and Piégay, 2001). The lag varies from 750 to 800 m for the 1826 land use types to 2.5–2.6 km for elevation. Because spatial autocorrelation is strong, sampling above these lags was not feasible in order to apply standard statistical tests; only 15–50 pixels could be extracted following this sampling design. Consequently, we used a sample for which the pixel values displayed autocorrelation. Therefore, parametric statistical tests were not used because of the bias of the *p*-value (e.g. too high degrees of freedom and underestimation of the variance).

In order to estimate how land use change was influenced by environmental variables, we performed a between-class Multiple Correspondence Analysis (MCA), also called barycentric discriminant analysis (Lebart et al., 1995). MCA is a type of correspondence analysis used for categorical data, i.e. each variable is coded for presence or absence. The preliminary table had 65 variables (64 for the 1956–1991 period), each corresponding to a modality coded 0–1 for each of the eight environmental variables, and 2500 pixels (the 20% sample). Each change in land use (e.g. pasture to forest) for each period was treated as a discrete class. Fourteen classes (types of land use change) were identified for the 1828–1956 period and 11 for the 1956–1991 period.

The aim of the between-class MCA was to identify linear combinations of environmental variables that enable us to differentiate classes of land use change, maximizing the inertia between the classes. The inertia is defined as the variance of coordinates of individuals (here the pixels) on a given factorial axis. The first combination (first factorial axis) has the largest between-class inertia, whereas the second combination, which is not correlated to the first, has the second largest between-class inertia. In order to validate statistically the dispersion of the centres of gravity for each of the different classes, a randomized test was computed (Manly, 1991). For each random distribution of individuals within the classes ($n = 000$), the total between-class inertia was calculated in relation to total inertia. All the calculations were completed using ADE® software (Chessel and Dolédec, 1996).

4. Results

4.1. Evolution of anthropogenic pressure on land

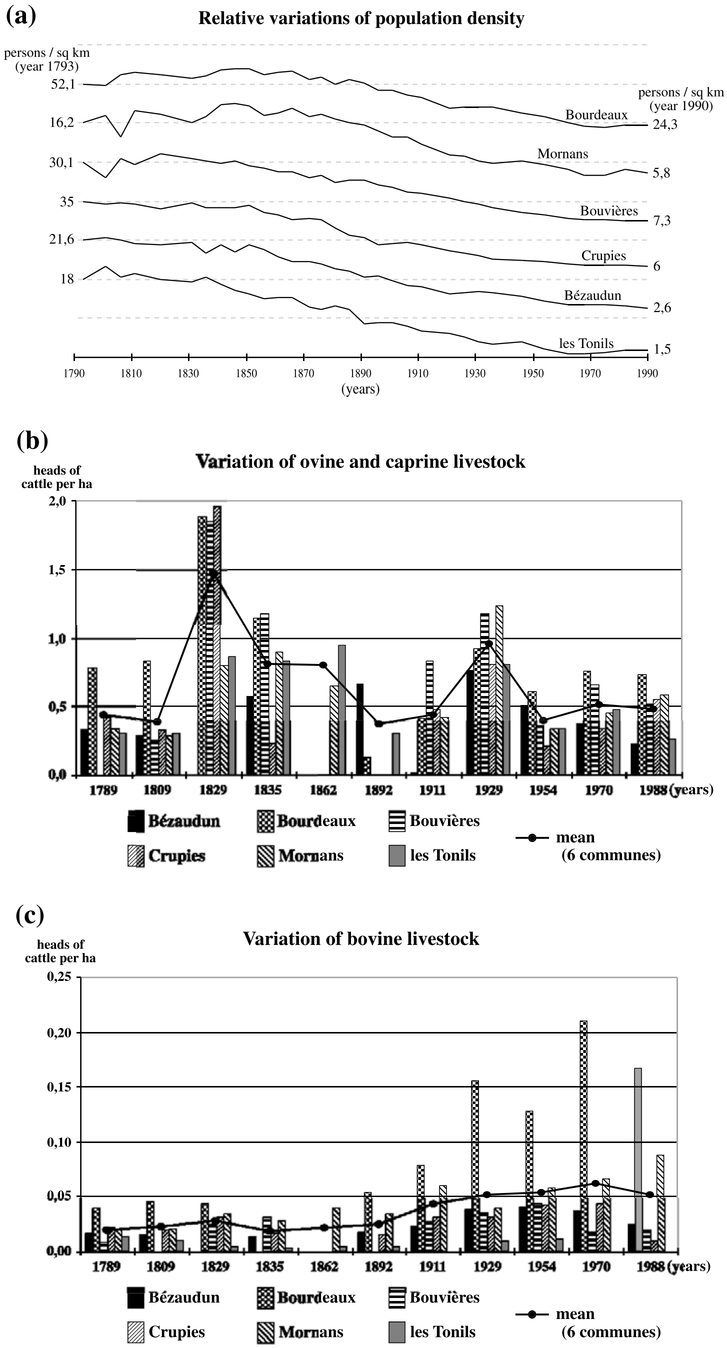
Demographic changes in population and livestock were interpreted as indirect indicators of land use change. Two types of behavior were observed within the communes of the pays de Bourdeaux (Fig. 3a). Bézaudun and les Tonils (Fig. 1a), like Crupies, a neighboring commune, underwent rapid depopulation soon after 1789. Densities in Bézaudun and les Tonils decreased by factors of 8 and 12, respectively, in the 200 years from 1789 to 1988. In contrast, the populations of other communes (Bourdeaux and Mornans) remained fairly stable until the end of the 19th century and then gradually declined. Bourdeaux is a small town that has been less affected by surrounding rural changes. However, the evolution of Mornans is unusual as it is a rural commune similar to Bézaudun.

Ovine (sheep) and caprine (goat) breeding is traditionally characteristic of dry mountain areas, where historic fluctuations in the livestock are often linked to economic and political events. Two periods seem to have been particularly favorable to ovine breeding (Fig. 3b). In 1811, a government policy encouraged ovine breeding to supply wool to rapidly growing industries, and this explains the increase between 1809 and 1829. During the first half of the 20th century, a second phase of renewed ovine breeding resulted from increased demand for lamb meat. Cattle raising was never of great importance in the Upper Roubion basin (Fig. 3c). The populations during the 19th century are mostly of draught animals. The growth in bovine density at the beginning of the 20th century corresponds to a progressive increase in dairy cattle.

4.2. Contemporary evolution of land use

The comparison of the three maps demonstrates that land use underwent major changes since 1828 (Fig. 4a and b). For the first period (1828–1956), the most significant changes

Fig. 3. Demographic evolution of population and livestock in the communes of the pays de Bourdeaux, notably les Tonils and Bézaudun (see Fig. 1 for location): (a) variations in population density per commune between 1790 and 1990; the curves express relative variations and are ordered according to tendency: for example, very strong decrease for les Tonils but later and less significant reduction for Bourdeaux; the left and right numbers give the densities of population for the beginning and the end of the period considered, (b) variation of ovine and caprine livestock densities in each commune between 1789 and 1988 and (c) variation of bovine livestock density in each commune between 1789 and 1988.



(a)
Relative variations of population density
persons / sq km (year 1793)
52,1
16,2
30,1
35
21,6
18
persons / sq km (year 1990)
Bourdeaux 24,3
Mornans 5,8
Bouvières 7,3
Crupies 6
Bézaudun 2,6
les Tonils 1,5
1790 1810 1830 1850 1870 1890 1910 1930 1950 1970 1990
(years)
(b)
Variation of ovine and caprine livestock
heads of cattle per ha
2,0
1,5
1,0
0,5
0,0
1789 1809 1829 1835 1862 1892 1911 1929 1954 1970 1988 (years)
Bézaudun
Bourdeaux
Bouvières
Crupies
Mornans
les Tonils
mean (6 communes)
(c)
Variation of bovine livestock
heads of cattle per ha
0,25
0,20
0,15
0,10
0,05
0,00
1789 1809 1829 1835 1862 1892 1911 1929 1954 1970 1988 (years)
Bézaudun
Bourdeaux
Bouvières
Crupies
Mornans
les Tonils
mean (6 communes)

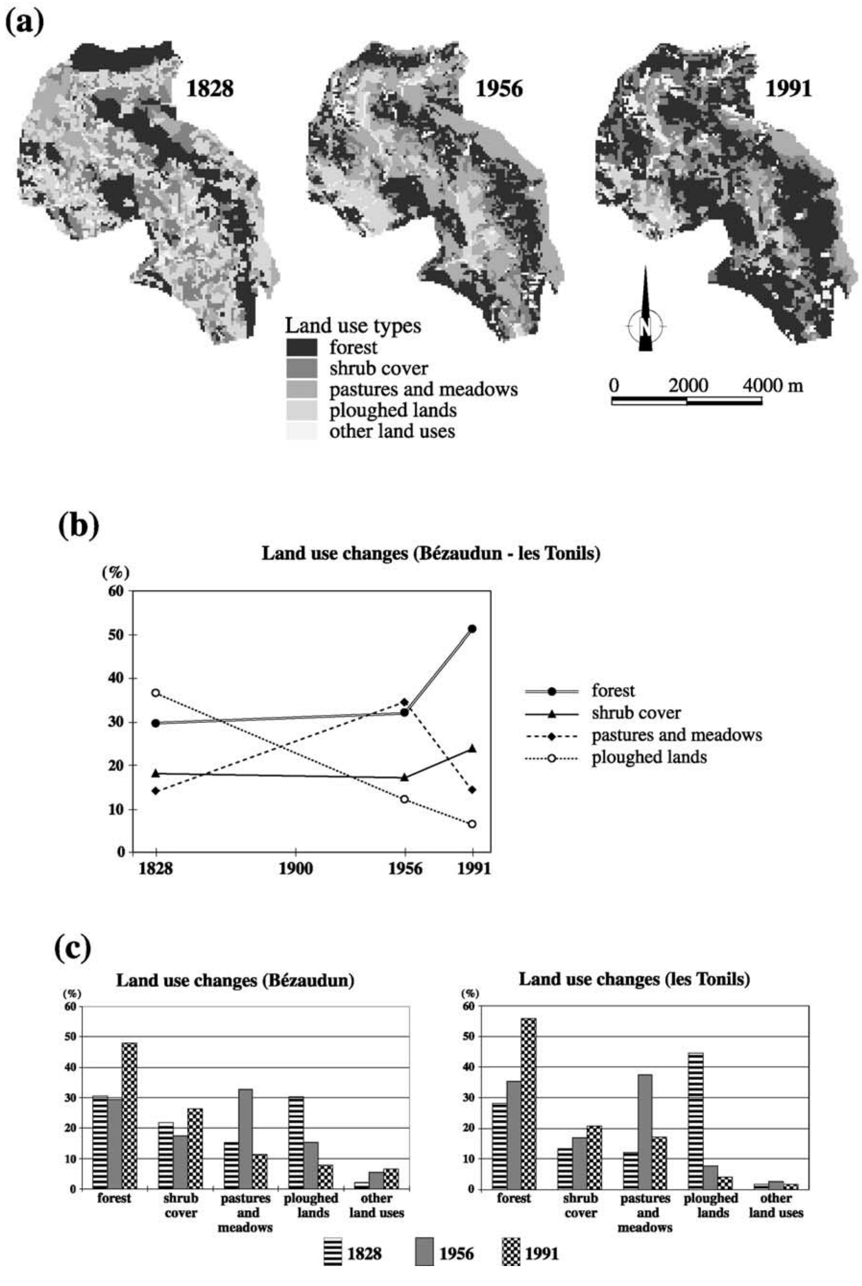


Fig. 4. Land use changes between 1828 and 1991 in the communes of Bézaudun and les Tonils: (a) land use maps of 1828, 1956 and 1991, (b) temporal evolution of surface areas occupied by land use types within the two communes and (c) distribution of the land use types in 1828, 1956 and 1991 in each commune.

were (i) the substantial increase in grazing, from 14% to 34.6%; and (ii) the large decrease in ploughed lands, from 36.4% to 12.1%. The areas occupied by the two other land uses remained relatively stable. However, this stability in terms of surface area does not rule out possible spatial redistribution of these land use types throughout the communes. The second period (1956–1991) was characterized by marked extension of forest (from 31.9% to 51.2%) and an increase in shrub areas (from 17.1% to 24%). The decrease in ploughed land observed during the first period continued after 1956. By 1991, it represented only 6.3% of the total area. Pasture areas decreased during the second period as much as they increased during the first.

The two communes did not follow exactly the same evolution (Fig. 4c). Between 1828 and 1991, les Tonils experienced a more marked decline in ploughed land, which disappeared almost completely by 1991. The evolution of grazing is more similar between the two areas, even though the commune of les Tonils maintained slightly more pasture lands. The most interesting contrast between the two communes concerns the evolution of forest area. The increase in forest area began earlier and was greater in les Tonils than in Bézaudun, essentially because of late 19th century voluntary afforestation by the Mountain Land Restoration (RTM) program to protect the slopes against erosion (130 ha in 1895).

Significant changes in parcel patterns were also observed on maps (Fig. 4a). Nineteenth century parcels were very small, mingling together various land uses to create an intricate mosaic. In contrast, the 1991 map shows that some land uses had disappeared (e.g. vineyards), whereas the main ones (forest units, shrub units, pastures) form large homogeneous areas.

4.3. Environmental variables and land use

4.3.1. Discrimination of the environmental variables on land use changes

Regardless of the time period, the between-class inertia is much less important than the inertia within each class. It is equal to 4.26% and 4.36%, respectively, of the total inertia for the 1828–1956 and 1956–1991 periods. This suggests that the environmental conditions existing within each type of land use change are strongly variable, with only a limited number of modalities contributing to the discrimination between these groups and others independent of them. However, the permutation tests for each period demonstrate that the variability between classes is statistically significant, as no random between-class inertia value in over 1000 random permutations was greater than the observed between-class inertia value (1828–1956, observed value = 0.31, simulated values vary between 0.035 and < 0.31; 1956–1991, observed value = 0.298, simulated values vary between 0.030 and < 0.29). In other words, certain environmental variables are strongly related to the different types of land use change. The first two factorial axes of each between-class MCA give a good summary of the entire between-class inertia, as they comprise 46% and 21% of the between-class inertia for the 1828–1956 period, and 53% and 19% for the 1956–1991 period. The following analysis is focused solely on these maps.

For the two periods, the environmental variables, particularly slope, elevation, bedrock lithology and surface deposits, discriminate land use change. These four variables show a widespread distribution on the first factorial map of the between-class MCA (Figs. 5a and 6a). The modalities of slope and elevation form clear gradients. Moreover, the resistant rocks (massive siliceous limestones, bedded siliceous limestones, bedded limestones, limestones and calcareous sandstones) and the soft rocks (both types of marls) are on opposite sides of the factorial map, whereas interbedded limestone and marl have intermediate positions. Siliceous limestones and bedded limestones at elevations between 1000 and 1200 m and with slopes greater than 31° are located in the same part of the factorial map. This first group of modalities contrasts with the second group composed of marls, gentle slopes and low elevations. Regardless of the period considered, surface deposits also contribute to the first axis in relation to bedrock classes. Modalities 9 and 10 (Table 1) co-occur with marls (modality 7).

(a)

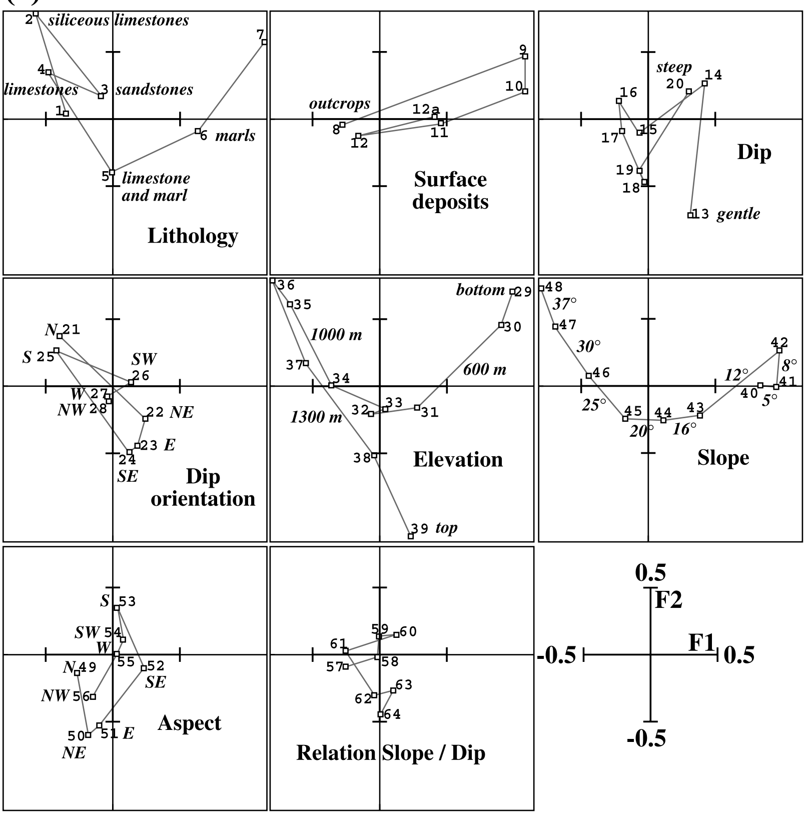


Fig. 5. First factorial map of the between-class MCA performed on the 1828–1956 data: (a) projection of the modalities of each environmental variable (see Table 1 for code meanings), (b) projection of the sampled pixels grouped according to types of land use change; the first number corresponding to the land use type in 1828, the second to 1956: 1 = ploughed lands, 2 = pastures, 3 = shrub lands, 4 = forest and 5 = other land uses, (c) land use types of 1828 and (d) land use types of 1956.

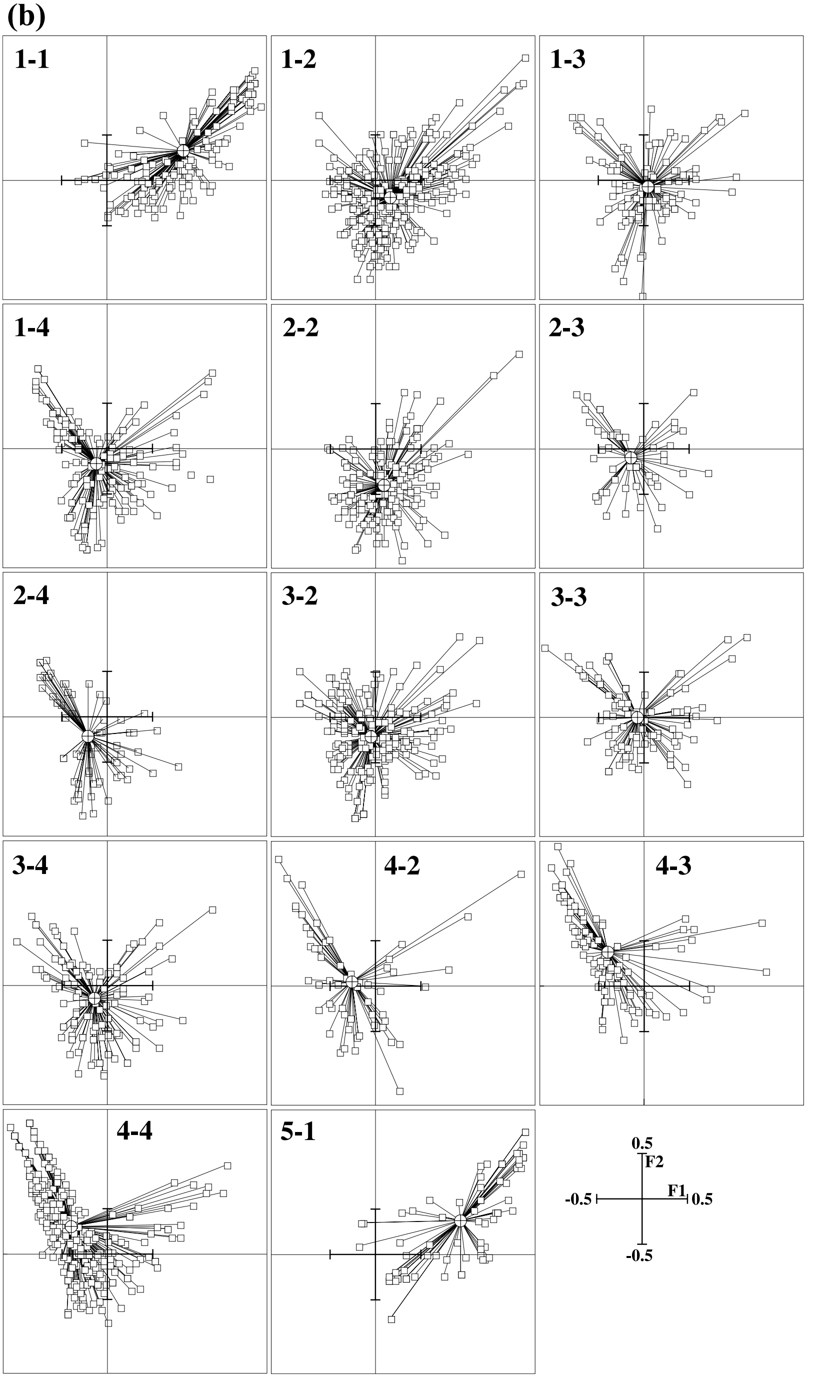


Fig. 5 (*continued*).

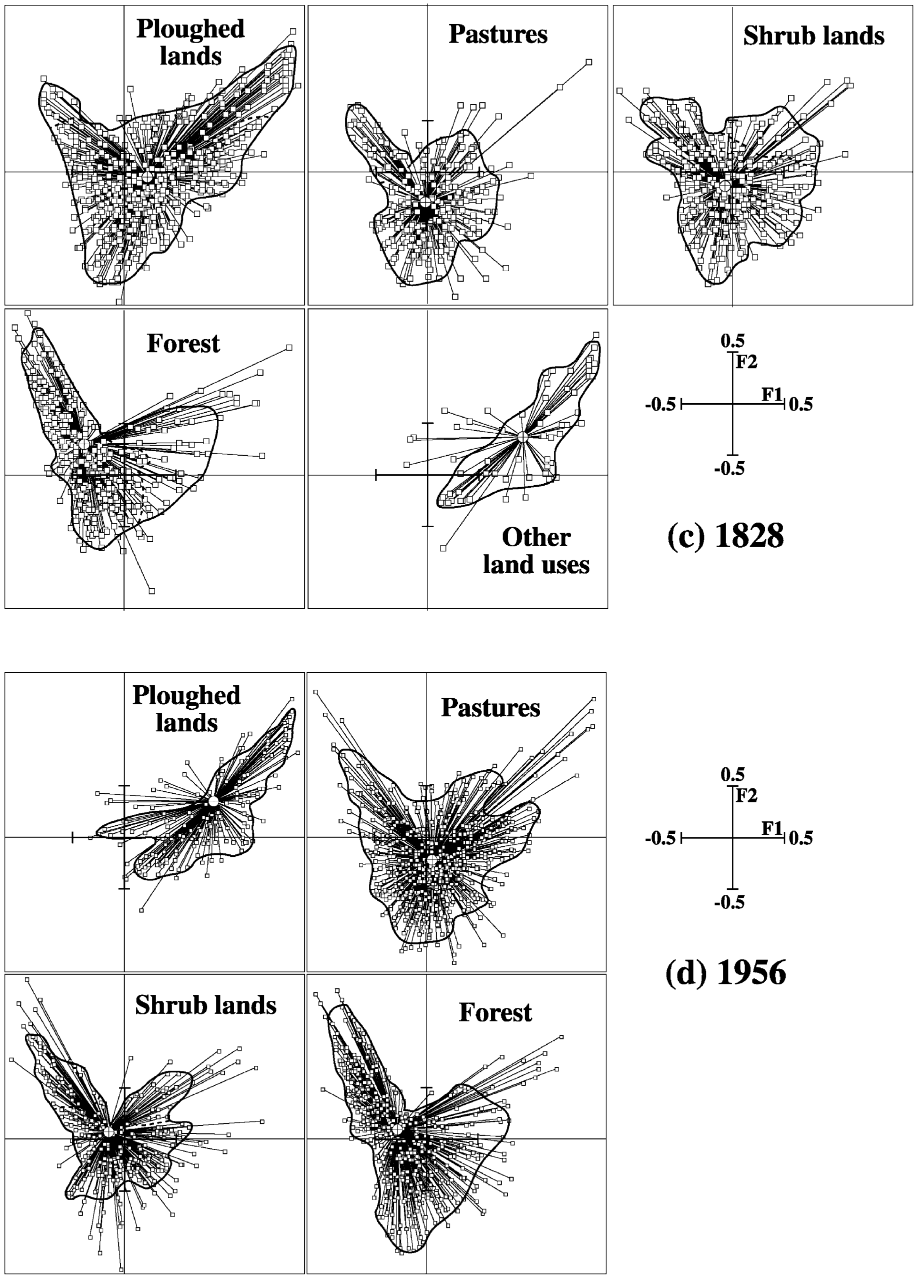


Fig. 5 (*continued*).

For the first period, other modalities also contribute to the second factorial axis such as a dip of 0–9° (modality 13) with dip of 50–69° (modalities 18 and 19), but also north–east and east aspects (modalities 50 and 51). They often co-occur where the elevation is over 1300 m (modalities 38 and 39). The other variables, notably relation between slope and dip, are much less discriminating. The scatters of land use changes (Figs. 5b and 6b) show that the influence of environmental variables is more important for the first period (1828–1956) than for the second (1956–1991). Moreover, Fig. 5c and d shows that the

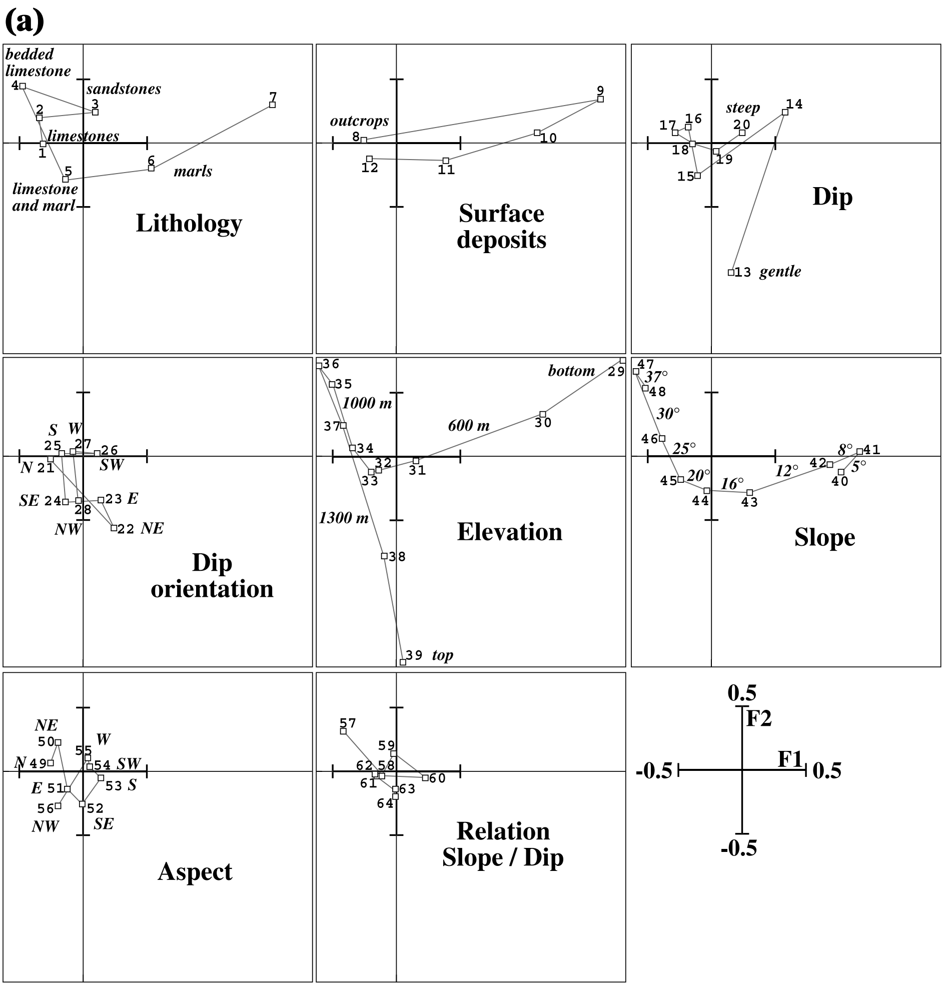


Fig. 6. First factorial map of the between-class MCA performed on the 1956–1991 data: (a) projection of the modalities of each environmental variable (see Table 1 for code meanings), (b) projection of the sampled pixels grouped according to types of land use change; the first number corresponding to the land use type in 1956, the second to 1991: 1 = ploughed lands, 2 = pastures, 3 = shrub lands and 4 = forest, (c) land use types of 1956 and (d) land use types of 1991.

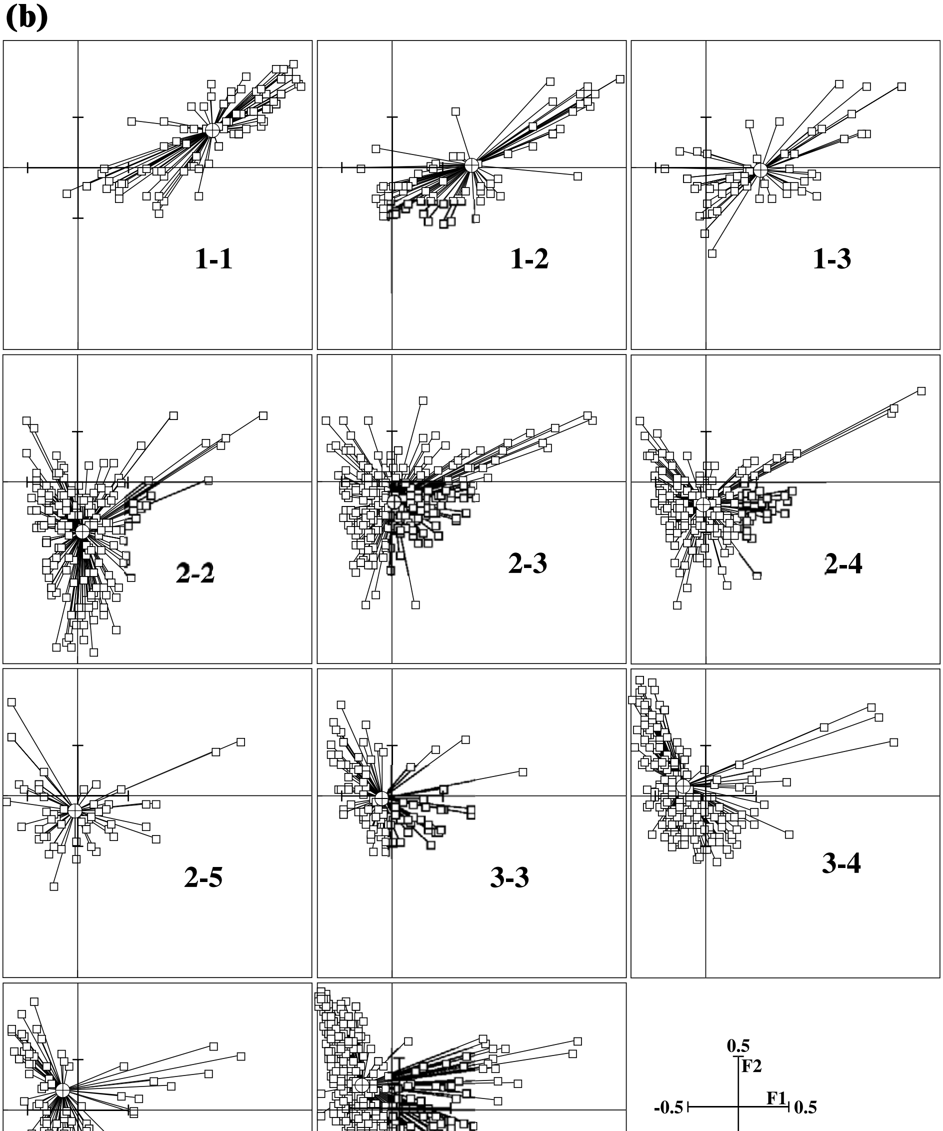


Fig. 6 (*continued*).

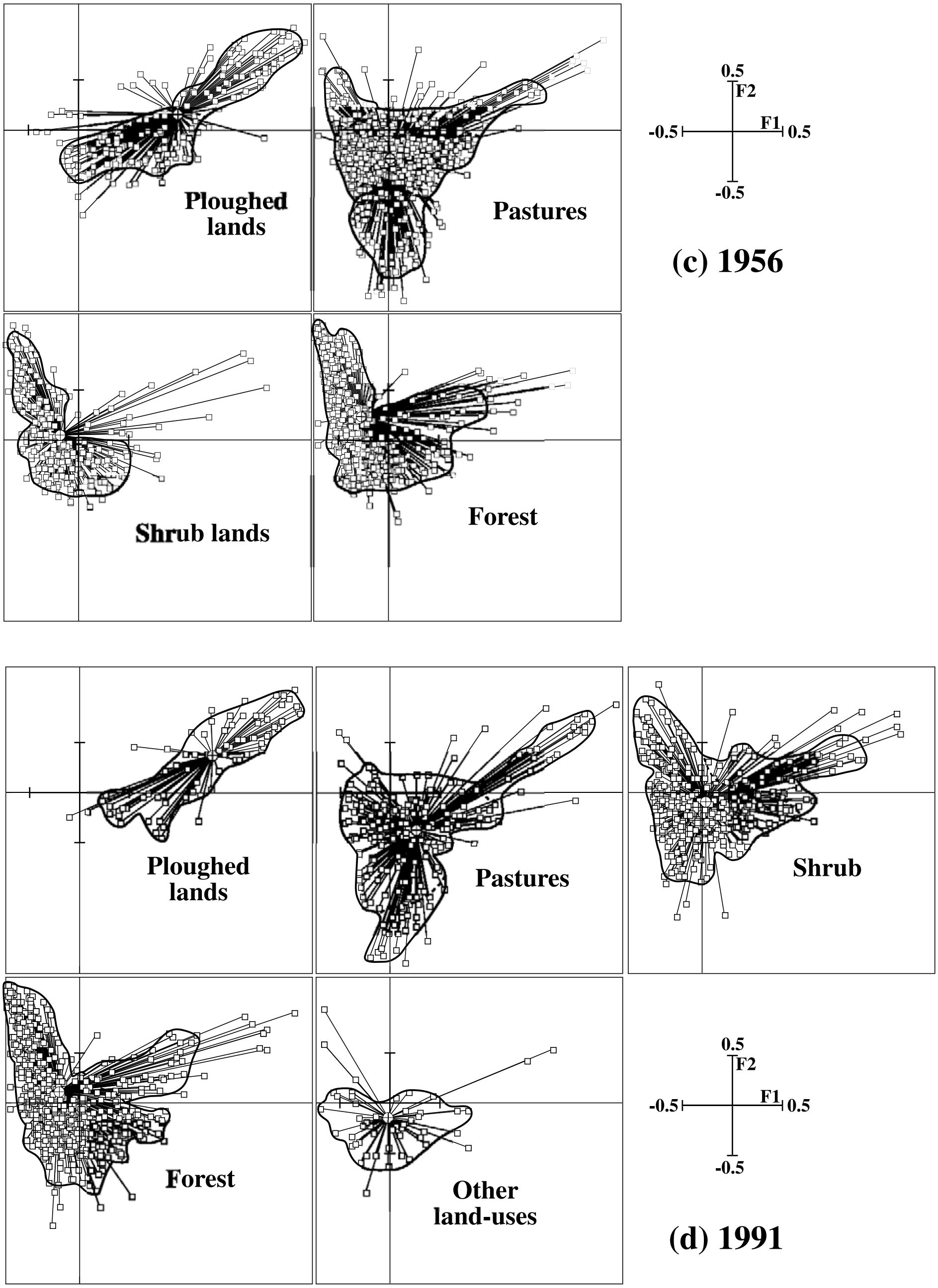


Fig. 6 (*continued*).

scatters of ploughed lands and shrub units changed considerably in shape between 1828 and 1956, whereas the shrub scatter displayed a marked change and the forest scatter only a slight change in the second time period (Fig. 6c and d). If we take the example of ploughed land change between 1828 and 1956, the scatters (couples 1–1, 1–2, 1–3 and 1–4) are located at different places on the factorial map, showing a clear influence of environmental factors (Fig. 5b). Ploughed areas are replaced by pastures, shrub units and forests, and these three types of changes (couples 1–2, 1–3 and 1–4) occurred in areas occupied by pastures (couple 2–2), shrub units (couple 3–3) and forest (couple 4–4), respectively. This demonstrates that abandonment of ploughed land was clearly linked to environmental factors. During the 1956–1991 period (Fig. 6b), changes in the plots of land use types are not as extensive as in the first period; the barycentres of the scatters (couples 1–1, 1–2 and 1–3) shift only slightly. This means that environmental variables did not greatly control ploughed land changes during the second period.

4.3.2. Period 1828–1956

In 1828 (Fig. 5), ploughed lands were widespread despite diverse environmental conditions, although they were absent from siliceous limestones and infrequent on bedded limestones. They were also uncommon at elevations of 1000–1200 and 1450–1500 m, which correspond to the sectors with very steep slopes. There were no ploughed lands on slopes >37°. However, ploughed lands were maintained on the summits (up to 1450 m) where slopes are not too steep. These observations suggest that slope was the key factor limiting the extent of ploughed lands, whereas elevation and bedrock lithology were not clearly limiting factors. In 1956 (Fig. 5d), the ploughed lands were distributed more uniformly in relation to particular environmental variables, including marl strata, all types of surface deposits except modalities 10 and 11, low elevations (400–700 m) and slopes < 16°.

In both 1828 and 1956, pastures were located in various environmental settings, but generally not where environmental conditions were best for ploughed lands (i.e. where elevation and slope are low), nor on the steepest forested slopes. In 1828, pastures and ploughed lands were in competition between elevations of 1300 and 1500 m on slopes < 25° (mountain of Couspeau, Fig. 1b). Between 1828 and 1956, pastures increased from 14% to 34.5% of the total area, because many ploughed lands were abandoned and converted to pasture (Fig. 5b, couple 1–2). The pasture scatter grew but conserved its initial positions and shapes (Fig. 5c and d). This means that most of the ploughed lands that changed to pasture were located in environmental settings similar to those of pastures, namely under relatively poor conditions for ploughing, and that farmers tended to abandon the least suitable land first. For both years, the central group is delimited by certain environmental characters that include elevations of 600–1000 and 1300–1400 m; slopes of 13–30°; interbedded limestone and marl; and absence of surface deposits (modalities 8 to 12). However, the scatter spreads more widely in 1956 on the right side of the graph, corresponding to areas of gentle slope, low elevation and with marl interbedded with limestone. Fig. 5b shows this displacement of the scatter of land use changes [1828 ploughed lands–1956 pastures (couple 1–2), but also 1828 shrub units–1956 pastures (couple 3–2) and 1828 forest units–1956 pastures (couple 4–2)]. The pasture areas extended very little into forest areas, but did extend into areas that were previously ploughed or shrub. This occurred mainly at elevations between 600 and 900–1000 m, but also at elevations of 1300–1400 m where slope ranged between 13° and 30°.

In 1828, the shrub units were broadly distributed through elevations of 600–1000 and 1200–1400 m, which corresponds to a range of average slopes (13–30°). The form of shrub scatter is superimposed on the pasture scatter. Both types of landscapes are used for grazing, but pastures form open herbaceous cover that is sometimes very degraded by gully erosion whereas shrub lands are composed of herbaceous and brush cover with *Buxus sempervirens*, *Genista cinerea*, *Spartium junceum* and *Pinus sylvestris*. As with the pasture, shrub units occupied marginal areas where farmers did not plough. For 1956, the shrub units formed a main scatter with two secondary prolongations on the upper right and left sides of the graph (Fig. 5d). The main part of the scatter is characterized by elevations of 600–1000 m, with slopes of 13–30°, calcareous sandstones and massive limestones or interbedded limestone and marl. The left prolongation corresponds to greater elevations (1000–1300 m), steeper slopes (>31°), siliceous limestone or bedded limestone and north and south dip orientations. The right prolongation overlaps environments that were traditionally ploughable lands (low elevation, gentle slopes and marls). Although the total area of shrub cover did not change between 1828 and 1956 (Fig. 4b), its spatial distribution did change (Fig. 5b). It increased on previously ploughed lands (4.8%) and forest (4.6%), as in the two prolongations discussed above, but it also diminished in favour of pastures (8.4%) and forest (5.0%) in other areas.

Forest location is clearly discriminated by environmental variables, but the scatter is complex, displaying two opposing branches. It did not change greatly between 1828 and 1956. The environmental characteristics associated with the main branch of the forest scatter are steepest slopes, elevations of 700–1300 m; resistant bedrock lithology; the absence of surface deposits except for two classes (modalities 10 and 11); dips of 20–49° west; and north–west, north and south dip orientations (Fig. 5c and d). The secondary branch shows that forests were also located on gentle slopes (13–16°) and at lower elevations (600–700 m). This secondary group was somewhat wider in 1956 than in 1828 and its extension introduced a tendency that accelerated between 1956 and 1991.

4.3.3. Period 1956–1991

The scatter of ploughed land environments contracted between 1956 and 1991 (from 12.1% to 6.3%), indicating that ploughed lands become even more restricted to specific environments (Fig. 6). In comparison to 1956, ploughed lands in 1991 no longer occurred at elevations of 600–700 m or on slopes of 13–20°. They occur in marly areas rather than interbedded limestone and marl. In 1991, ploughed areas are located at very low elevations, on the gentlest marl slopes and in the most productive agricultural areas. Almost no overlap exists between this scatter and those of the other land use types.

Pastures strongly decreased between 1956 and 1991 (from 34.6% to 13.9%) but occupied an environmental setting very similar to that of 1956. At most, there was isolated disappearance of pastures in sectors characterized by siliceous limestone, with slopes of 26–30° and elevations of 1200–1300 m. Within the two communes, pastures were replaced by shrub lands in 12.4% of the study area, and by forest in 10.2% (Fig. 6b, couples 2–3 and 2–4).

The scatter of shrub units clearly widens on the right and lower sides of the graph (Fig. 6c and d). In contrast to 1956, the shrub units in 1991 occupy areas characterized by marl interbedded with limestone, two classes of surface deposits (modalities 8 and 9), elevations of 550–650 and 1250–1350 m and gentle slopes (0–12°). Shrub lands extended primarily into what were previously pasture areas, as well as into some previously ploughed areas (Fig. 6b, couples 2–3 and 1–3). These extensions indicate a pioneer response of natural vegetation to rural abandonment. In consequence, the shrub scatter can be superimposed on the forest scatter, so that the two types no longer appear to be differentiated by environmental controls but rather by intrinsic features and vegetation age. Although the shrub unit environments were similar to those of pastures in 1828, they showed greater resemblance to those of the forests in 1956 and 1991.

Forested lands show the most significant change, colonizing the largest portion of the territory (from 31.9% to 51.2%). Although the main forests were inherited from the first period, the scatter greatly extended into the right side of the graph, shifting the barycentre of the scatter. Forests spread into areas with elevations of 550–700 and 1300–1350 m, slopes of 13–16° and on marl interbedded with limestone and interbedded limestones, mainly at the expense of shrub units (10.2%) and pastures (10.2%) (Fig. 6b, couples 3–4 and 2–4).

5. Discussion

5.1. Causes of land use changes

In the first half of the 19th century, demographic pressure and economic needs caused farmers to maximize cultivation. Ploughed lands were widespread, despite unfavorable environments. They occupied 36.4% of the studied areas and extended up steep slopes. Thus, nearly 30% of ploughed lands was located on slopes >22° with 3.5% on slopes of 31–37°, even though no terracing was practiced. These areas presented many drawbacks including low fertility, ploughing difficulty, risk of erosion and poor accessibility. On the summits (1200–1450 m), where slopes were not too steep, the ploughed lands extended at the expense of mountain pastures. Rather than maintaining quality pasture and despite the short cultivation period and distance from the farmhouse, farmers had no choice other than to cultivate as much land as they could. Plant species in these areas had to be hearty and require little upkeep. Efforts were concentrated on satisfying basic family needs under conditions of food autonomy (the farmers were self-governed and produced most of what they needed). At the same time, political decisions encouraged the development and improvement of ovine breeding, inducing a strong increase in livestock population. Because farmers were not able to reduce the area of ploughed land, pasture pressure was also exerted on the shrub and forest units. Forest materials were used for timber and combustion, as winter fodder (trees leaves) and as fertilizer on the most productive ploughed lands (use of shrubs like *B. sempervirens* as well as leaf litter and humus). Forests were located where no ploughed lands or pastures could be established. Generally, shrub units corresponded to environments where slope processes (overland flow and mass movements) prevented tree growth. Pastures also extended to these inadequate environments, where overland flow was very intense (e.g. the badlands of Bézaudun). In both cases, soils became so degraded that land taxes were decreased to a very low rate. Nevertheless, the distinction between shrub units and pastures was not really based on environmental criteria, explaining why shrub and pasture scatters were so strongly superimposed for the 1828 land use. In the early 19th century, the difference between pastures and shrub units was explained by the period or the intensity of land use. In principle, both of these types would have corresponded primarily to previously ploughed lands, but the areas that were abandoned longer ago or were not subject to pastoral pressure converted to shrub areas.

Between 1828 and 1956, cultivated areas decreased markedly (from 36.4% to 12.1%) and became limited to the most favourable soils. Pastures increased from 14% to 34.5%; 14.1% of the territory evolved from ploughed lands to pastures and 8.4% from shrub units to pastures. These changes are explained by a major transition in the agricultural system (Taillefumier, 2000), in which the self-sufficiency of the 19th century was replaced by an agro–pastoral system oriented towards lamb breeding (Sauvan, 1937). Lamb production was supported by railroad development, mineral fertilizers and artificial fodder, enabling the region to develop economically. Thus, in 1956, the inhabitants continued developing strategies to gain maximal profit from land. Consequently, the forest areas had not increased since 1828 and still occupied the least fertile areas.

Between 1956 and 1991, the abandonment of ploughed lands continued, but at a slower pace than between 1828 and 1956. However, physical constraints no longer influenced the location of ploughed land. Parts of productive agricultural areas, although suitable for modern cultivation, were also abandoned. Moreover, many pastures were spontaneously colonized by shrub formations, probably a pioneer stage of forest growth. For the first time in nearly two centuries, forested areas extended significantly. This resulted from farmland abandonment, a process that has accelerated since World War II (Meyzenq, 1984; Jauneau, 1990; Mesclon, 1991). The traditional outlets for ovine breeding have diminished since the 1980s, and it is now difficult to develop other specific kinds of production (orchards, lavender and vineyards). As in the other neighboring mountainous regions, many farms have been abandoned. Given the difficulty in establishing outlets, mountain farming cannot currently penetrate competitive national or international markets. The only possible exception is the production of beef cattle for breeding in the communes of Bourdeaux and Mornans, subsidized by the Common Agricultural Policy (CAP) (Fig. 3c).

5.2. Environmental variables that discriminate land use changes

Eight variables were used to study how environmental factors influenced land use changes. Generally, elevation, slope gradients, bedrock lithology and surface deposits best discriminated the spatial distribution of different land uses and the land use changes. In the 19th century, slopes that were too steep were the only real limiting factor in the extension of ploughed lands. Thus, slope was the principal limiting factor, and elevation and bedrock lithology were only secondary factors. GIS analysis confirmed the absence of ploughed lands on slopes >37°, and showed that some areas were cultivated on slopes of 31–37° (3.5% of the total of the ploughed lands), and that slopes >22° represent almost 30% of the total cultivated areas. This last percentage is much greater than the rates observed in two mountain regions of Spain, where ploughed lands on slopes >22° represented < 10% of the total cultivated area (Arnáez-Vadillo et al., 1990). Our results are especially remarkable given that there was no cultivation on terraces in this area. The evolution of pastures between 1956 and 1991 also confirms the importance of slope as a physical factor for controlling land use changes. Pastures disappeared on slopes of 26–30°. Because the need for pastures decreased at the end of the 1956–1991 period, farmers abandoned the steepest areas that were least productive.

Aspect, dip, dip orientation and the relationship between dip and slope explain very little of the spatial distribution of the various land uses studied. For aspect, this is surprising, as it is clearly an important factor in many mountainous areas. For example, it strongly discriminates land use patterns between the adret (warm, sunny slopes) and ubac (cooler, shaded slopes) in the Northern Alps (Rambaud and Vincienne, 1964) and Southern Alps (Darracq, 1992; Gautier, 1994). In two Spanish mountains areas (Arnáez-Vadillo et al., 1990), the influence of aspect depends on regional climatic context: in the Cameros Viejo, north-facing slopes, where less evaporation occurs, are cultivated to a greater extent (30.7% in adret vs. 37.1% in ubac), whereas in the colder and wetter Aragon Pyrenees, adrets are cultivated more (52.4% in adret vs. 13.7% in ubac). In our study, the lack of influence of aspect may reflect the small area involved and thus the incomplete range of aspects. Almost 80% of the chosen study area is orientated west to south–west. In the Diois and Baronnies regions, only a few communes, generally located in small breached anticlines, present a range of contrasting aspects. These communes demonstrate better the relationship between aspect and land use (Gautier, 1994).

The effect of dip on hillslope processes such as the transfer of runoff or groundwater is well known at the local scale. However, its influence on land use, and more importantly on the decisions of farmers who determine land uses, is more difficult to evaluate in relation to other more evident environmental factors. In 1828, shrub units, pastures and ploughed lands occupied areas with strong, often opposite, dips (50–69°), corresponding to interbedded limestone and marl and eroded hillslopes (Fig. 5a and c). This particular area is well identified on the second axis corresponding to the heart of the pasture/shrub unit scatters. Callot (1978), Barthès and Callot (1980) and Decoud (1983) considered dip as a significant factor partly regulating the circulation of water and the rooting depth of vegetation, so it may influence the establishment and development of vegetation communities. On the other hand, Darracq (1992) and d'Épenoux (1992) interpreted dip only as a secondary factor. However, all these authors agree that the relationship between dip and slope is of greater importance than dip itself. Indeed, this relationship controls morphological, hydrological and biological processes. Our results indicate that the relationship between dip and slope has affected land use change, but it does not in itself explain the distribution of the major land use types. The 1828 data demonstrate that such areas could be ploughed, even if they were unstable. In 1956 and 1991, they were mainly occupied by pasture, suggesting that it was difficult for trees to become established. A previous study based on field surveys showed the influence of the relationship between dip and slope on geomorphologic processes (Liébault et al., 1998). We conclude that these variables influence land use by limiting tree establishment, but when the demands on land are high, such areas can also be ploughed.

At times of high demographic pressure (19th century) or very low pressure (end of 20th century), land use was not well related to the environmental factors considered. When agricultural demands were high, farmers ploughed almost all areas regardless of soil quality, except on the steepest slopes with siliceous and interbedded limestone. Forest, if not restricted by human activity, can establish spontaneously almost everywhere in the region, except on the most unstable slopes. In contrast, when agricultural demands are very low, forest and pre-forest shrub extended widely, regardless of environment conditions. Any remaining cultivated plots were then probably related to historical, pragmatic and social considerations (land appropriation, inheritance, distance to the farm and landscape conservation for patrimonial reasons) rather than to environmental factors. In both periods, environmental factors did not greatly influence land use, but rather controlled species diversity. Between these two extremes, as in 1956, farmers were more inclined to adapt their agricultural practices to the environmental context, as well as to socio-economic factors.

5.3. Effects on the landscape

During the period studied, landscapes became simpler. At the beginning of the 19th century, the landscape was characterized by a fine and varied mosaic of traditional farming areas combining multiple land uses. In contrast, by the late 20th century, such fine-grained diversity had disappeared, with forest, shrubs and pastures forming larger homogeneous areas. This tendency is likely to increase if it is not controlled by the maintenance of agriculture. In 1991, 24% of the study area was occupied by waste lands and shrub formations. Sooner or later, given local conditions, these secondary formations will evolve to forest stages, first to pine forest (*P. sylvestris* and *Pinus nigra*) and then probably to oak (*Quercus pubescens*) or beech (*Fagus sylvatica*) groves. Assuming the current trend to reduced agricultural and pastoral demands continues, current shrub cover will probably evolve to forest. Although it is risky to make landscape forecasts in the absence of additional analyses (Brossard et al., 1993; Joliveau, 1994; Josselin, 1995), it is possible that within 20–50 years, this process could lead to a landscape consisting of extensive wooded areas enclosing a few cultivated areas, with some pastures located near summits or hillslope bottoms. This projection may well apply to many communes in the Diois and Baronnies mountains and more generally to much of the mountain regions of Europe (Arnáez-Vadillo et al., 1990; Barbéro and Quézel, 1990; Brossard et al., 1993; Dérioz, 1993; Molinillo et al., 1997), leading to or intensifying territorial management and development problems.

Fischesser (1991) noted that the rural landscape has become a consumer product that should be taken into account in rural development strategies. Under the combined effects of modern economy and technology, traditional diverse rural landscapes are changing rapidly, becoming more standardized and homogeneous. In some regions, where forest management has caused landscape degradation, Fischesser (1991) suggested ways for reconciling economic development and landscape conservation. Tourism development often supplements and helps to renew agricultural activities, but could suffer from such an evolution of the landscape. This is particularly true in the Diois and Baronnies regions where tourism activities, because of the attractiveness of the landscape, have become a major source of income in the two last decades.

5.4. Effects on the hydrosystems

Landscape afforestation has changed sediment routing through stream networks. Significant channel changes have been observed on the two streams (Bine and Soubrion) draining this area during the last 50 years (Liébault and Piégay, 2001). Diachronic analysis of aerial photographs has shown that the active channels of these streams narrowed, primarily between 1956 and 1971, as riparian vegetation encroached on formerly active channel surfaces. Although a similar trend is observed on the two streams, the Bine shows stronger in-channel vegetation development during this period, mainly because active gravel bars were more developed in the 1950s than in the Soubrion stream. These differences in channel morphology suggest that the Bine stream received a greater and more persistent bedload supply through the 1950s.

This contrast can be related to a difference in the chronology of land use change in the two catchments. To explore this hypothesis, we classified land use types in terms of protective and non-protective covers. Forest, shrub and herbaceous covers were considered as protective land use types, whereas ploughed lands, orchards, vineyards and bare soil were considered non-protective. In both catchments, protective land use cover increased as a result of farmland abandonment, but there were some differences between the two (Fig. 7). In the Soubrion catchment, the increase in protective cover occurred more rapidly, because at the beginning of the 19th century, this catchment was very degraded; protective and non-protective land uses occupied almost the same total areas. In 1956, protective vegetation already covered 90% of the catchment, and there was no significant later change. Protective cover increased more slowly in the Bine catchment. In 1826, protective vegetation already covered 70% of the catchment; it increased to 80% in 1956 and 86% in 1991. Thus, in the Bine catchment, there was a slight increase in protective vegetation (1.6 ha year^{-1}) between 1826 and 1956, and a greater increase (3.2 ha year^{-1})

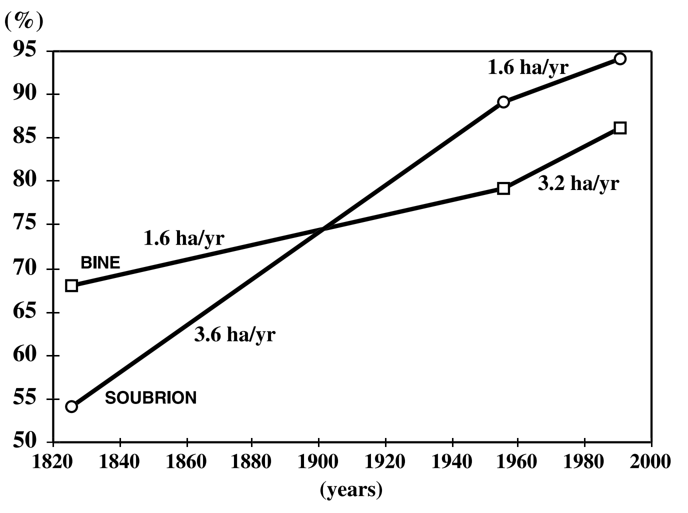


Fig. 7. Evolution of protective vegetation in the Soubrion and Bine catchments.

between 1956 and 1991, but in the Soubrion catchment, there was a greater increase (3.6 ha year^{-1}) in the first period and only a slight increase (1.6 ha year^{-1}) in the second.

This suggests that the channel metamorphosis of these streams was partly linked to the progression of vegetation cover on the hillslopes. The earlier extinction of the Soubrion creek is well correlated with early and more rapid vegetation development, and is partly explained by torrent control works (planned afforestation of the end of the 19th century) on the main degraded areas of the catchment. Conversely, the persistence of wide gravel bars in the 1950s on the Bine stream can be explained by: (i) a weaker increase in protective land use types between 1828 and 1956; and (ii) persistence of large badland areas still supplying sediment to the channel (where no soil conservation was applied). Active channel narrowing observed during the last 50 years is strongly correlated with the rapid progression of forest cover between 1956 and 1991. This observation is confirmed by others made within various neighboring catchments and also in systems located to the north (Liébault and Piégay, 2002). Such examples illustrate how the depopulation of mountain areas can have major effects on channel geometry that mask the more gradual effects of climate change. In our opinion, more research is now needed in Europe to improve understanding of the real effects of climate change on channel geometry, primarily at the end of the Little Ice Age (1850–1880). It is difficult to differentiate climatic from anthropogenic factors during periods in which mining, land use change and channel regulation also occur.

6. Conclusions

The landscapes of European mountains have changed greatly over the last two centuries because of the industrial and agricultural revolutions. Farmers took into account environmental conditions (primarily slope and elevation, but also bedrock lithological conditions) during the first part of the 20th century to select the best area for a given land use and bolster the efficiency of the traditional agro–pastoral system. But environmental factors were considered in a less discriminating manner by farmers when human pressure was either very high, as in the 19th century, or low, as in the post World War II period. In the setting of the sub-Mediterranean middle mountains, environmental conditions seem to have been partially limiting factors for land use, but human controls have been more critical.

The land use changes have had environmental and societal consequences. Decreased sediment transfer has narrowed and degraded downstream channels producing negative economic consequences by undermining infrastructures and decreasing water resources. These changes also led to closing and simplification of the landscape, which is not necessarily welcomed by local populations and decision-makers, because the loss of traditional humanized landscapes may compromise developing tourist activities.

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