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Resilience of Terraced Landscapes to Human and Natural Impacts: A GIS-Based Reconstruction of Land Use Evolution in a Mediterranean Mountain Valley

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Highlights:

- Terraced lands are a historical landscape under risk in Mediterranean mountains;
- Their surface and land-use trajectories are analyzed across five centuries in a GIS;
- Although mostly abandoned, they persist in the ground landscape;
- Their environmental and productive functions are part of their future resilience.

Abstract: Terraced historical landscapes have multiple functions in mountain land, limiting erosion, enabling agricultural production and constituting cultural heritage. Currently, they are largely abandoned in Mediterranean regions and facing the ongoing impacts of climate change. Our aim is to reconstruct the evolution of land use on the terraces in order to test the hypothesis of the resilience of these landscapes and their age in recent history (17th–21st century). To achieve this, we used various current and archive spatial datasets and GIS knowledge to detect and map terraces and the changes in land use. We tested this hypothesis in a territory impacted by a recent extreme event, facing the challenge of its reconstruction. Our main outcome showed that the optimal use of the terraces corresponded to the demographic optimum of the mid-19th century, and they were gradually abandoned after the Second World War, with significant differences between Mediterranean and mountain lands. Despite this evolution, the terraces persisted and withstood an extreme event, validating our resilience hypothesis and opening avenues for the revitalization of this territory based on this heritage. These findings are drawing perspectives for the future of terraced landscapes in Mediterranean mountains in the context of climate change.

Keywords: lidar; historic maps; past and future resilience; climate change

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1. Introduction

"The landscape is part of the land, as perceived by local people or visitors, which evolves through time as a result of being acted upon by natural forces and human beings" (https://www.coe.int/en/web/landscape/the-european-landscape-convention, accessed on 1 April 2023). From this perspective, the resilience of historical landscape has to be understood as the result of interactions between natural and anthropogenic drivers over time. Terraced landscapes are a good example of resilience of historical landscapes, because they have been maintained until the present time despite important environmental and socio-economic changes. These landscapes have received increasing attention in recent years as cultural landscapes have been threatened by agrarian abandonment [1–3], as have their functions of hydro-climatic regulation, food production, and preservation of natural and cultural heritage, both tangible and intangible [4]. This issue has been renewed by the notion of resilience, applied to socio-ecological landscapes [5] and traditional agro-systems [6], and the ability to overcome disturbances, assessed over the long term and more recently in the context of the acceleration of history. These disturbances are materialized by the occurrence of extreme meteorological events (droughts, floods) attributed to climatic irregularity, particularly in the Mediterranean region. In the past, the Little Ice Age and irregular rainfall were combined with land clearance and overgrazing during the demographic maximum ("torrential crisis") [7–12]. More recently, these extreme events have been attributed to global warming [13], and their frequency is expected to increase in the future [14,15].

Agricultural terraces should be considered to be "nature-based solutions" in response to climate change [4] [https://www.iucn.org/our-work/nature-based-solutions, accessed on 1 April 2023]. Indeed, they may regulate natural processes, even though they rely on human labor for the good quality of their construction, appropriate drainage and maintenance. They contribute to carbon storage [16] and the reduction in erosion when the soil is covered with vegetation and not saturated [17–19]. Agricultural abandonment can lead to degradation and the reactivation of erosive processes [10,17–19], even if the degradation of dry-stone walls is not always related to the stage of the vegetal succession [20]. This abandonment mainly concerns the terraces furthest from the villages [21]. Their rehabilitation is costly [22], but it helps to restore agro-biodiversity and the spontaneous biodiversity of the orchard's herbaceous stratum [20,23]. The resilience of this historical heritage is, therefore, a major challenge in mountainous regions facing the impact of climate change, even though they are relatively depopulated [24–27].

To address this issue, it is important to detect terraced areas and trace their historical trajectories using appropriate methods. The analysis of changes in land use, in particular in terms of historical forms of land development such as terrace-based development, requires the provision of spatially accurate field information [28,29]. Unfortunately, topographic maps rarely contain information about terraces and their land use. It is often presented in a conventional way, which does not reflect the real estate, enabling, e.g., the calculation of the surface and length of terraces. Moreover, the use of satellite and aerial images limits the detection of terraces to areas not covered by shrub and tree vegetation [29] and periods after the 1950s [25,26]. Old maps and land registers provide information on land use prior to the 1950s, without necessarily identifying terraced areas [3]. Several authors have retraced the evolution of forested areas since the 18th or 19th century, using properly georeferenced and cautiously interpreted old maps [30–32]. Other studies focused on the evolution of agricultural surfaces based on comparison between old cadasters and aerial photography (1950s to 2000s) [23,32,33]. These studies evidence significant differences in the evolution of land use in Mediterranean mountain regions, according to their market integration and demographic changes.

To detect the topographic signatures of anthropogenic structures such as terraces, remotely sensed high-resolution LiDAR data (Light Detection and Ranging) based on laser scanning technology provide detailed information on terrain surfaces [19,34,35], including terraces overgrown by trees or covered by the soil surface [36]. The spread of LiDAR technology has enabled significant advances in archaeology, particularly in forested areas, revealing the roles of ancient societies in shaping and developing their territories long considered "wild" or "virgin" [37,38]. In Mediterranean Europe, the mapping of terraces has been exhaustive in Italy, with Lidar data making it possible to complete pre-existing mapping work based on other sources to calculate the surface area by region and estimate the lengths of the terraces (Ferrarese et al., in [2]). In France, qualitative terrace mapping based on aerial photographs [38,39] can now rely on the progressive provision of LiDAR data by the French National Institute of Geographic and Forest Information (IGN).

By mapping the terraced plots and their historical trajectories since the 17th century, we aim to verify the hypothesis of the resilience of these historical landscapes and draw lessons for their future. We assume that despite human and natural impacts across 5 centuries, terraces maintained and are bringing ecosystem services in a high-risk environment. The hypotheses have been applied in a valley presenting a diversity of landscapes and facing the challenge of rebuilding the territory in a post-disaster context, drawing potential lessons for other Mediterranean valleys under risk due to climate change. In addition to scientific knowledge, our study aims to contribute to the decision-making process regarding the rehabilitation of terraces by residents' associations and professional and hobby farmers [22]. For this aim, Lidar data are associated with cartographic, photographic and historical sources in a multi-source and multi-date approach, thanks to the use of GIS and statistical processing.

2. Materials and Methods

2.1. Study Site

Our study site, the Roya valley, is a cross-border catchment located in the Maritime Alps (France, 636 km^2) and Imperia Province (Italy, 69 km^2), flowing into the Mediterranean Sea (Figure 1). It has very steep slopes along a bioclimatic gradient, from the Mediterranean Sea to alpine domains (maximum altitude 2755 m). These mountains, forming an orographic barrier, are a source of intense rainfall events, particularly in the context of climate change. This valley is a representative case of Mediterranean-montane terroir, raising the question of resilience, and it is, therefore, particularly rich in lessons.

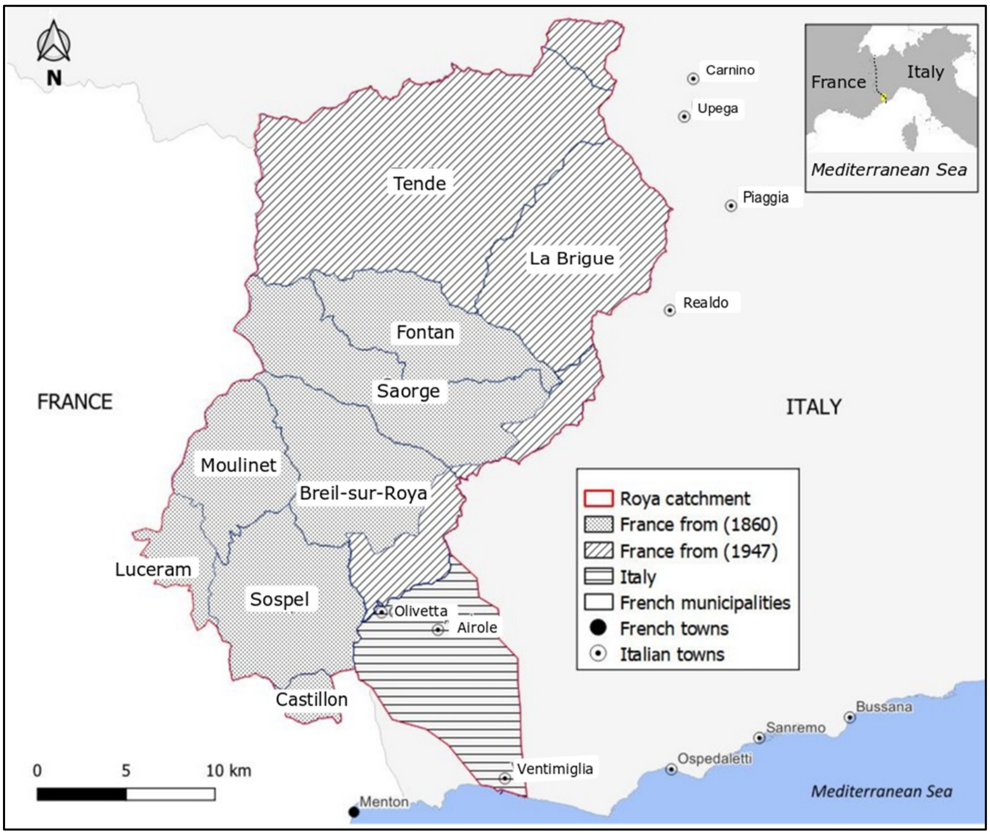

Figure 1. Location map. The Italian towns Carnino, Upega, Piaggia and Realdo were part of La Brigue before 1947. Realization by T. Le Vot.

The Roya valley was occupied by man from proto-historic times to the Middle Ages at the subalpine level and from Antiquity at the montane level [40]. Tangible remains of ancient breeding activity niversité Paris Cité.1983.2107; are still visible in the landscape (https://www.vermenagna-roya.eu/fr/patrimoine/enclos-de-la-causega/, accessed on 1 April 2023). In this work, we extend the study area to the entire French watershed and reduce the time scale to the last five centuries, based on map sources. During this period, the Roya valley was part of the County of Nice that alternated between its attachment to France and the kingdoms, duchies or principalities that made up part of Italy before 1860–1870 [41,42].

In 1860, the middle part of the Roya valley became French, while the upstream part and mouth remained in the Kingdom of Sardinia. There was a significant increase in population (+69%) between 1793 and 1861 (Cassini.ehess.fr, accessed on 1 April 2023, Table S1), a period that corresponds to the demographic peak observed in Mediterranean rural territories [27], a trend amplified here by the easing of military conflict. Although varied, agricultural production was not considered self-sufficient at the time of the demographic peak [43,44], particularly in northern municipalities highly specialized in breeding (Tables S2 and S3).

After the 19th century, the rural economy diversified from agriculture and forestry to other activities (tourism, energy, mine, hay marketing [43,45]; Table S4). The smallest and most remote municipalities underwent strong depopulation, particularly after the Second World War (the population was divided by four), while it was maintained in the most important urban nuclei that are well connected with Italy and the Riviera (−45% on average). In 1947, the eastern and upstream part became part of France, while the mouth remained Italian (Figure 1). Since the 2000s, there has been a slight demographic revival in all the municipalities, but most of the population did not participate in an agricultural activity in 2020 [https://www.insee.fr/fr/statistiques/2011101?geo=DEP-06, accessed on 1 April 2023]. Agriculture w specialized in mixed farming or poly-livestock farming (https://vizagreste.agriculture.gouv.fr/#/indicateur/06/2020, accessed on 1 April 2023).

Throughout this history, several violent climatic events occurred, especially during the Little Ice Age. Periods of intense hydrologic activity in the Rhône valley (1551–1600, 1651–1700, and particularly 1701–1710) alternated with periods of calm (1601–1650) [46]. This chronology corresponds partly with the 500–1000-year-old deposits found in the Roya valley [47,48]. In Southern France, erosion and torrential activity stages remained intense until the end of the 19th century, linked to the demographic maximum [9]. They decreased with the development of dams and reforestation from 1860 onward, after two important floods in 1840 and 1856 in the Rhône Valley (Table S4) [8,9,45]. During the 20th century, only two intense events occurred (1926 and 1952, a maximum of 200 mm/day) in the Roya Valley (http://pluiesextremes.meteo.fr/, accessed on 1 April 2023). This period corresponds to a decrease in the width of the river channel and forest reclamation.

In October 2020, Storm Alex, amplified by global warming and the moisture reserves of the Mediterranean Sea, hit the Roya Valley (663 mm in one day) and caused extensive damage, particularly to the road network and infrastructure concentrated on the valley floor [49]. This was exacerbated by the uprooting of trees that formed ice jams [50]. The valley was profoundly transformed, becoming unrecognizable to local residents, with a wide active strip filled with coarse sediments, tree trunks, vehicles and ruins. Farmers were affected by the storm: loss of land, displacement of herds, communication difficulties for many months and even the death of a shepherd trying to save his sheep occurred. Following 2020, after three years of drought, Storm Aline occurred in October 2023, fortunately being less intense than Storm Alex (200 mm/day). It is now the local people's turn to get involved and find original ways to rebuild the area and the valley's economic fabric, following a major investment by the French government to restore networks. The event has strengthened local solidarity, supported by several associations and groups of residents. In this context, the agricultural terraces represent the area's cultural and natural potential. They are an innovative nature-based solution for thinking and acting in a resilient territory [4].

2.2. Materials

2.2.1. Terrace Mapping

Three databases of the French National Institute of Geographic and Forest Information (IGN) were used and analyzed in a GIS for terrace mapping in the French Roya catchment via reasoned and multi-criteria photo-interpretation (Table 1).

Table 1. Materials used for terrace and land-use change mapping. Georf: georeferenced; Topo: topography.

Date	Name	Author [Source]	Scale	Georf	Topo	Land Use	Forest	Gaps
1672–1675	Carta generale de stati di sua Altezza Reale	Cartographer GT. Borgonio, [www.gallica.fr, accessed on 1 April 2023]	1/90,000	no	rough	Intercrop, tree-crop	No	Eastern slopes
17th	Engravings (Saorge and Tende)	GT. Borgonio [www.archives06.fr, accessed on 1 April 2023]	ND	no	rough	Detailed	No	no
1749–1754	Carte géométrique du comté de Nice	Engeneer P.J. Bourcet [https://www.servicehistorique.sga.defense.gouv.fr/le-shd-en-france/vincennes-centre-historique-des-archives, accessed on 1 April 2023]	1/14,400	no	rough	Intercrop, crop, tree-crop	No	Western slopes, northern limit
1850	Carta topografica degli Stati in terraferma di S. M. Il Re di Sardegna	Royal staff corps [https://www.defense.gouv.fr/academ/membres-lacadem/bibliotheque-lecole-militaire, accessed on 1 April 2023]	1/50,000 Sheet no. NLXXXI	no	regular	Crop, pasture, wood, olive, vine	Yes	no
1864–1866	Napoleonic cadaster	French State, [www.archives06.fr, accessed on 1 April 2023, 40]	2500	yes	no	Crop, pasture, wood, olive, vine	Yes	no
1947–1951	Aerial photography	IGN [www.geoservices.ign.fr, accessed on 1 April 2022]	1/40,000	yes	no	Visual interpretation of the proportion of the plot covered with scrubland and forest		no
2023	BD TOPO, Zone de Végétation		1/25,000	yes	no			Crops, pasture, orchards in 2020
2023	Plots of land		1/25,000	yes	no	No		no
2020	Lidar HD post-Storm Alex		DEM 1 m resolution	yes	good	No		no
2023	Lidar HD 06			yes	good	No		no

- LIDAR HD

LiDAR data were used to detect the layout of terraces in the French Roya catchment. LiDAR HD point clouds came from aerial LiDAR acquisition with densities of at least 10 pulses per m^2 and 5 pulses per m^2 above a 3200 m altitude. Using class no. 2 of the classification attribute of LiDAR data (laser beams reflected from the ground), a Digital Elevation Model (DEM) with a spatial resolution of 1 m was created by the authors. The DEM enabled the generation of a shaded relief model, which made it possible to visualize terrain microforms in terms of the terraces (parallel stripes), disregarding the trees above ground level. Lidar may be generated with a different sun inclination to improve micro-topography detection. All output data were saved in *asc format. The above task was conducted using SAGA GIS© 3.6.2 software.

- Plots of land layer

To avoid confusion between terraces and natural shapes, the elongated and narrow shapes of plots of land layers were a first clue, because terraces were built perpendicularly to the slope within this frame, which corresponds to the property of the landowner who invested labor, materials and expertise in the construction and maintenance of the terraces in order to obtain significant harvest. A small square plot, corresponding to a permanent or seasonal habitat (small house or hut), is often associated with clusters of terraces, testifying to the need to have a place to rest or store equipment during agricultural work on plots far from the village, the low distance to habitat being observed as a favorable factor in the literature [21,38].

- Aerial photography 1947–1951

These images give an image of traditional land use at the beginning of the rural depopulation that followed the Second World War, the abandonment of agriculture and the development of tourism [2,3,22,23,25,45]. Terraces are recognizable via aerial photography when they are delineated by white dry stone walls, which generate a white-striped texture (Figure S1) or a dark grey-striped texture as a function of slope illumination. Aerial photography was largely used to check our interpretation of terraces based on a couple of Lidar-plots of land (Table 1).

- Data analysis in a GIS

The Lidar layer was overlaid in a GIS, using Qgis 3.6.2© software, with the plots of land layer, which gave the frame of land use. Plots of land carved into terraces were selected with a multi-selection tool and identified automatically in the attribute table of the plots of land layer with the raster calculator. When terraces were occupying only part of the plot of land, a new polygon was created, following the design of the terraces. The other part of the plot was generally plain and in very few cases covered with rock blocks (Figure S1) or shaped by a ravine. This methodology is time-demanding, although very cautious and without error. It is similar to those used to map terraced land in Italy [2]. These criteria should be integrated into an automatic mapping process, based on algorithms, and compared with the results obtained with reasoned photo-interpretation. It is the same for the calculation of the total length of the terraces, which requires an accurate and automatic method (in progress).

2.2.2. Land-Use Change Mapping

- Building a multi-date geographical database

Our study is based on the conception of a multi-date geographical database during the period 17th–21st century (Le Vot, unpublished master thesis), with different images giving information of variable precision about past and current agricultural land use (Table 1). Except for the Napoleonic cadaster, which provides information on the land-use history of each parcel of property, the other sources provide this information in the form of areas with figurative colors or letters. Land use in the oldest maps is not described in the legend and has been interpreted (Figure S1).

- Old maps analysis

Ortho-rectification of the oldest maps proved impossible due to the projection errors made (Table 1). For this reason, the boundaries of cultivated areas were identified based on the geographical information available in our database (topographical map, the DEM, slope values, hydrographic network, roads and habitat visible on aerial photographs of 1947–1951). To compensate for the spatial imprecision of the oldest maps, we selected only terraced plots present in the area designated as "cultivated" because they were most probably cultivated. The information about land use is more or less detailed (Table 1, Figure S1). We considered that terraces described as "wood" correspond mainly to chestnut groves [40]). Timber harvesting was carried out on large plots of land every 50 years [43], whereas terracing is better suited to annual fruit picking.

- Napoleonic cadaster

The land use was described in 1864–1866 in the mid and southern catchment by the Napoleonic cadaster, realized after the region's attachment to France in 1860 (Figure 1, Table 1). This map was georeferenced following Bonne's projection with the reference coordinate system ESRI 53024, adapted to old maps [51], with Arcgis Pro 3.2© software.

The current shape of terraced plots was edited to fit with the one of the Napoleonic cadaster. This work was carried out plot by plot, for each land-use type, and further merged in a synthetic layer. Following previous studies [40], we considered that "pastures" referred to a large and plain plot, without terraces, freely grazed by the herd during the summer and generally distant from the human habitat. Terraced plots that are referred to "pasture" in the Napoleonic cadaster were probably meadows used for hay production or grazed during spring and autumn [43].

- Aerial photography 1947–1951

Land use during the 20th century is documented by aerial photography from 1947–1951 (Table 1) because this period is representative of the beginning of rural abandonment in Mediterranean mountains [2,3,29]. The abandonment of terraces was mapped plot-by-plot via multiple selection, considering two forest reclamation stages, the early (tree cover 10–49%) and mature stages (tree cover >50%). Additionally, we considered the spatial arrangement of trees to identify the first reclamation stage (colonization front, irregular arrangement of trees) and scrubland cover and to avoid including in this category plots with regular arrangement of trees, corresponding to intercropped system.

- BD TOPO 2023

During the 21st century, the vegetation layer of the BD TOPO 2023 (IGN) gives the following information about land cover: the different types and densities of forest and scrublands and vine and olive groves. Because of gaps (Table 1), the automatic method of intersecting plot centroids with this layer created errors. The plot-by-plot method was applied to extract the information about the dominant land use in the terraced plots. Despite being time-demanding, this method uses the same criteria as the analysis of the photography of 1947–1951.

- Data criticism

Comparisons of the surfaces of terraced plots at different periods of time must be considered with caution, because each cartographer followed their own rules (Table 1). To minimize the gaps existing in the Borgonio and Bourcet maps, we created a merged attribute, considering cultivated terraced plots mapped either by one or by both authors. The Napoleonic cadaster was used to calculate the property taxes, and for this reason, it may underestimate the forest cover and the frequency of intercrop. The topographic map was established by the Royal Staff Corps to describe the entire Kingdom of Sardinia. The cover of groves has not been updated in the BD TOPO 2023 since the 2000s (pers.com, Laurence Jolivet, IGN). This map is less accurate than the high-resolution photo-interpretation at the land-plot level in the municipality of Sospel [23].

2.3. Data Analysis

The information about the land use of terraced plots is available in the terraced plots layer for five periods: 1672–1675 (Borgonio), 1749–1754 (Bourcet), 1850 (topographic map) or 1864–1866 (Napoleonic cadaster), 1947–1951 and 2000–2023. Mapping with Qgis 3.6.2© software was followed by data analysis with Excel 2016© software. The data analysis had two objectives. The first objective was to compute the repartition of the terraced plots and land-use change in the French Roya valley. For this aim, pivot tables were realized to compute the surfaces of terraced plots, detailed by municipality, land use and period.

The second objective was to map and analyze the trajectories of land-use change for terraced plots. For this aim, we created a new attribute summarizing the change in or persistence of land use for each terraced plot. The land use described during the 19th century was the most precise, and it was, therefore, used as a reference. The abandonment of terraced chestnut woods was only considered if resinous or mixed forests were present in 2023, following field observations. A new attribute, named 17–21, with five letters corresponding to the five dates, was generated with the Concat function of Qgis 3.6.2© software. The 332 categories were further merged in 24 categories, with three letters, the first corresponding to the seniority of the terraces (17th and/or 18th century), the second to land use during the 19th century, and the third to evolution during the 20th and 21st centuries. Swinging trajectories (conversion from intercrops or vine in the 19th century to olive groves in the 21st century, or rehabilitation after the 1950s) were described separately. Intercrops were simplified to reduce the number of categories. The same simplification was applied for the elaboration of the legend of the map (Figure 2).

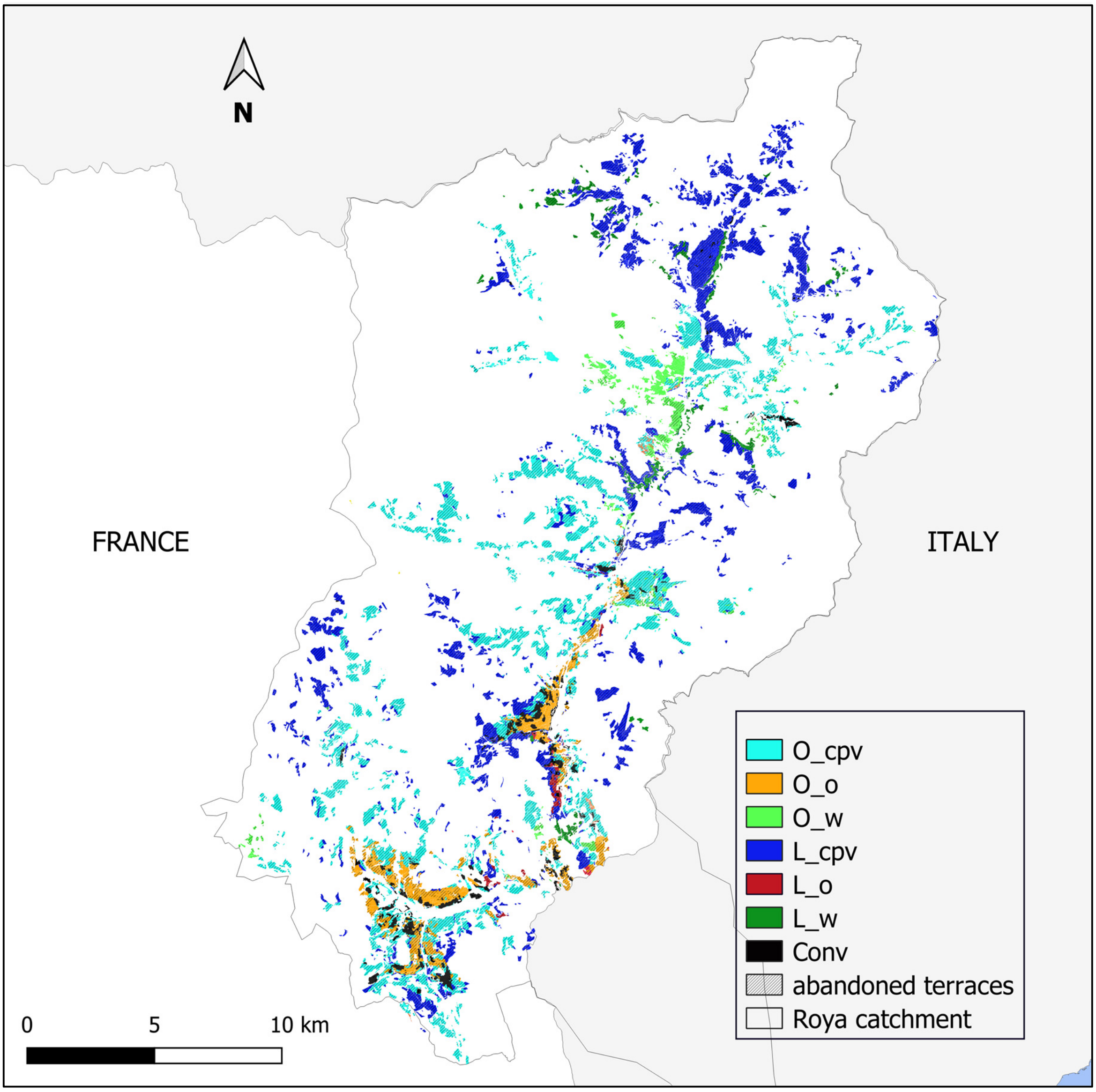

Figure 2. Land-use trajectories of terraced plots during the period 1680–2023 in the French Roya catchment. 0: old (17–18th century); L: late (19th century); cpv: crops, pasture or vine; o: olive; w: chestnut wood. Sources: Borgonio map, Bourcet map, Topographic military map, Napoleonic cadaster, aerial photography 1947–51, plots of land and BD Topo 2023 (IGN). Realization: T. Le Vot.

Different colors were given to the main land uses during the 19th century, depending on their seniority. Stripes were added for abandoned plots. Despite being time-demanding, this method is better adapted to the variable size of the terraced plots, partially covering the surface of the catchment, compared with cellular automata, based on a fixed size of continuous pixels [52].

3. Results

3.1. Terraces and Land Use

In total, 29,445 terraced plots have been identified in the French Roya catchment, covering a surface area of 90.8 km^2, corresponding to 14.26% of the whole catchment and 14.96% of the seven main municipalities. The total length of the terraces has been estimated to be 9000 km, following the literature [2], representing an important potential legacy. The average size of the terraced plots varies in a range from 0.23 ha (Breil-sur-Roya) to 0.41 ha (Moulinet). Sospel, the southernmost municipality, has the highest proportion of surface in terraces (28.3%), followed by Breil-sur-Roya (20.3%), Fontan (16.9%) and Moulinet (14.7%). The northernmost and largest municipalities, covering 60% of the catchment, have a lesser surface proportion of terraced plots (La Brigue, Saorge and Tende, around 11%). This suggests a gradient of increasing surface of terraces from the mountainous northern municipalities to the Mediterranean southern municipalities.

The comparison between the areas occupied by cropped terraces in the French Roya during the period suggests a dramatic increase from the 17th to the mid-19th century, doubling every century, followed by a decrease beginning in the 1950s (−33% in a century) and accentuating dramatically in 2023 (−73% in half a century) (Table 2). Considering the merged attribute (1680–1750), the total surface that was cropped in 1672-75 and/or 1749-54 was 57.70 km^2. Only one sixth of the cultivated areas during the 19th century persist in the 21st century (−81%), the abandonment being more notable in La Brigue, Fontan, Saorge and Moulinet and less dramatic in Breil-sur-Roya and Sospel (one third abandoned).

Table 2. Surface areas of cultivated terraced plots and total surface area of the municipality (in km^2). Period: 1672–2023.

Municipality	1672–1675	1749–1754	1850–1864	1947–1951	2020–2023	Total Surface Area
Tende	3.09	6.96	20.28	15	4.69	177.47
La Brigue	3.63	4.89	10.66	6.9	0.73	91.77
Fontan	3.70	3.86	8.45	5	1.35	49.61
Saorge	4.27	7.60	8.77	5.7	1.46	86.78
Breil-sur-Roya	2.76	7.41	16.43	11.5	3.85	81.31
Moulinet	3.34	1.70	6.08	2.8	0.30	41.07
Sospel	5.80	14.13	17.72	11.8	4.26	62.48
Total	26.62	48.79	90.8	61.1	16.86	636.46

During the 19th century, the terraces were cultivated with cereals, forage and groves (olive, vine, chestnut, fruit trees) organized along the bioclimatic gradient (Table 3).

Table 3. Surface of different land uses on terraced land in the Roya Valley in the 19th century (in km^2).

Municipality	Crops	Pasture	Chesnut	Vine	Olive	Intercrop
Tende	6.6	2.0	2.6	0.1	0	0.6
La Brigue	9.1	0.4	1.3	0.9	0	0.1
Fontan	13.0	1.6	1.3	1.4	0.1	0.2
Saorge	6.5	0.4	0.1	2.5	0.5	0.2
Moulinet	10.5	2.7	0	1.0	0	0.1
Breil-sur-Roya	10.8	0.9	0.9	2.4	4.8	1.8
Sospel	11.9	2.2	0	4.1	8.6	1.2

This was due to the decreasing heat needs of olive trees, vines and chestnuts, which are growing, respectively, in Mediterranean, temperate and mountain climates, with these differences also having a strong effect on the natural flora [53]. Despite the specialization in olive-growing and breeding according to the increasing latitude, land use was diversified on terraced plots.

3.2. Trajectories of Land Use

As expected, the abandonment trend is the most frequent case (85% of the total surface, Table 4). Other trends are detectable depending on the seniority or land use of the plots. Terraces mapped in the 17th or 18th century are still more frequently cropped than the additional terraces mapped in the 19th century. This suggests that the terraces built during the demographic maximum have been more widely abandoned (91%) than the oldest ones (81%) and are now almost completely covered with open or closed forest. Parts of the oldest terraces maintained or even increased across the period, particularly with half of olive grove being maintained (50%), one fifth (21%) thanks to either conversion, intercrop abandonment or renaissance. Half of chestnut woods (46%) still maintained. Conversely, cereal crops have decreased drastically (93% abandoned), even on old terraces, though their previous extension gives an idea of the potential surfaces available to develop local food production after clearing the ligneous species. Vineyards almost disappeared (99.8%), particularly in La Brigue, though this has been documented since the 17th century. It is the same for pasture located in Tende, as observed since the 19th century (95% abandoned).

Table 4. Land-use trajectories of terraced plots in the French Roya catchment (in ha). Period: 1672–2023.

Trajectory		Land Use	Breil s/Roya	Fontan	La Brigue	Moulinet	Saorge	Sospel	Tende	Total
since 17–18 th centuries	abandoned	chestnut	21	1	31		30	1	134	217
		crops	334	334	380	243	485	543	273	2591
		olive	122	4			50	317	0	493
		pasture	29	44	1	56	34	104	34	302
		vine	123	25	78	38	160	167	21	613
	cropped	chestnut	4	12	2	1	7		176	202
		crops	21	15	7	4	9	26	38	119
		olive	143	0			4	166		313
		pasture	1	4				5	4	15
		vine	0		1			0	0	1
		conversion	127	12	27	5	11	142	16	341
since 19th century	abandoned	chestnut	24		43		0		117	184
		crops	457	238	403	122		125	778	2123
		olive	34	3			5	15		58
		pasture	48	30	37	55	3	27	294	496
		vine	25	35			9	16	1	86
	cropped	chestnut	22	53	37	1	1		37	152
		crops	7	12	3		1	3	48	74
		olive	13				0	2		15
		pasture	0		0		0		19	20
		conversion	26	3	1	1	0	2	10	43

The map evidences the site-specific historical trajectories (Figure 2). The most remote parts of the catchment were cultivated later (striped dark blue) than those near the Roya and Bevera rivers. Old olive groves are persisting on the slope facing the villages of Sospel and Breil-sur-Roya. Parts of them have been abandoned, with others rehabilitated, in different positions on the slopes in these two villages. Old chestnut woods have been maintained on almost the whole slope overlooking Saint-Dalmas-de-Tende. On the contrary, the slope facing the village of La Brigue that had been covered with vineyards since the 17th century is abandoned, according to the BD TOPO 2023.

4. Discussion

This discussion is organized in five sections. First, we compare our results with the literature on terraced land and land use in the Roya Valley, in surface, time and space; second, we discuss how far this spatiotemporal organization validates our hypothesis of the resilience of historical landscapes. Finally, we recall the uncertainties in our results and suggest ways of reducing them.

4.1. How Many Terraces?

The surface area occupied by the terraced plots is supposed to correspond to the following cropped areas: vine, olive, cereals, fruit trees and meadows, and for this reason, we compare our findings to the estimations of cropped surfaces during the 19th century. The proportion of the surface of terraced plots that we found, almost 15%, is three times higher than the estimations of Fodéré (1801, [43]) and twice as high as estimates dating from 1874 [43] in the French "County of Nice". It is nearer to the inventory of Durante made at the time of the Kingdom of Sardinia in 1846, even if it probably overestimates the proportions of crops (14%) and meadows (11%) [cited by 43]. The highest proportions of terraced plots in Sospel and Breil-sur-Roya are consistent with the literature [44,53,54] and their Mediterranean-type agriculture.

Our innovative methodology, based on a multi-source photo-interpretation, including Lidar data, brings more precision than the use of outdated aerial photography [2,38,39]. Our findings are inferior to the cover estimated via photo-interpretation (30 to 50%) in the Maritime Alps and the Var [38], and the highest cover—28.6%—is found in the southernmost municipality of Sospel. They are superior to the cover of 10% considered representative of the whole Roya valley ([1], Blanc in [2]) and 8% in the Italian region of Liguria [2]. These lower proportions are nearer to those found by our mapping process in the northernmost municipalities specializing in breeding activity (La Brigue, Saorge and Tende, around 11%). These differences are explained by the non-exhaustive nature of previous studies and the lack of Lidar data. In conclusion, the legacy of terraced plots is important, considering its surface and length in the Roya Valley, and representative of the heterogeneity of this territory.

4.2. Time Variation

- 1672–1749

The increase in terraced land during the period 1672–1749 may be due to two different causes. First, we assume that the strong hydrological activity [9], combined with the increase in cultivated surfaces between the Borgonio and Bourcet maps, may explain the braided form of the confluence of the Roya–Bieugne–Lavensa rivers mapped by Bourcet in 1749–54 (Figure 3), despite the mitigation effect of the terraces on geomorphic processes. The presence of terraces, as well as their functions, were reported in 1736 ("To take advantage of the mountains on the left where there is a little land, they formed amphitheatre steps to support them and prevent the waters from carrying them away") [55]. The increase in terraced surfaces occurred during the military conflict between the Kingdom of France and the Duchy of Savoy (Kingdom of Sardinia after 1720), with severe consequences in Sospel and Breil-sur-Roya (plague, smallpox), as well as Tende and La Brigue (seasonal migration) [54]. Despite a decrease in the population noticeable in the first French Census (1793, https://www.departement06.fr/de-la-population-et-des-causes-de-sa-diminution-37200.html, accessed on 1 April 2023), the anthropogenic pressure was mostly due to the obligation of producing locally food for the population [42,54,56].

Second, the increase in the surface of terraced land is partly due to an underestimation of the cultivated areas by Borgonio and Bourcet, both in the shaded slopes and at the limits of the catchment. The intercropped landscapes mapped by Borgonio and Bourcet do not give an exhaustive idea, and the landscapes that retained their attention probably have a specific meaning that we have ignored. The large scale (Borgonio) and the context of a military campaign (Bourcet) are possible explanations for the gaps existing between these maps. The merged attribute is giving a more realistic assessment of formerly terraced plots.

- 1749–1850

Between 1749 and 1850–1866, the increasing trend in terraced land cover (+86%, +57% by considering the merged attribute) is partly linked to the demographic increase (+69%) that occurred between 1797 and 1861, as is true in rural French territories [27]. According to the literature [57], ten square-kilometers of terraces can be built in half a century if the demographic and economic conditions are favorable. This estimation is lower if compared with the extension of terraces between Borgonio's map and the mid-19th century maps (64.18 km^2). When considering the merged attribute 1672–1749, the increase, 36.1 km^2, in approximately 150 years is more consistent with this rate [57]. Most works agree with this chronology [2], while another author considers that terraced landscapes were already built in the 18th century or even before in the Roya valley [58].

Figure 3. Braided river at the confluence between the Roya, Bieugne and Levensa rivers, Saint-Dalmas-de-Tende. Source: Bourcet map, 1749–1754. Green lines: river; red: town and roads; green dots with orange lines: intercrop; light brown: uncultivated.

- 1850–1947

This period has been more frequently studied in the literature [2,3,25,32] thanks to the availability of historical sources. As in other Mediterranean mountains [3,25], the abandonment process began in the 1950s, or even before in the Maritime Alps [45]. The forest reclamation trend (33%) is probably due to the demographic decrease (−45%) during the past century and the Second World War (the war was violent, with destruction and military campaigns). The development of trade between France and Italy, following the new division of the territory (1860) [43] and the development of transport infrastructures (Col de Tende Tunnel in 1882; railway lines in 1928), with a resultant decline in self-sufficiency, are other explanations for the decrease in cultivated terraces, as observed in other studies [2,3,23,25,32].

- 1947–2023

Many authors have underlined the importance of the decline of traditional agriculture and the incentive towards modernization that produced the abandonment of terraced land in mountainous regions [2] and, more generally, of agricultural activity except in regions where agricultural production has intensified with market integration [3,6,25,26]. During that period, the population of the Roya Valley maintained at a low level until the 1980s and then began to recover, increasing slightly from the 2000s onward. Yet, the number of farmers probably followed the downward trend (-88%) observed in the Maritime Alps since the 1970s (https://vizagreste.agriculture.gouv.fr/#/indicateur/06/2020, accessed on 1 April 2023). For those reasons, three quarters of terraced plots were abandoned (72%) during this period, a value among the highest observed in the Mediterranean and mountainous European regions [2,3,6,25,26].

4.3. Spatial Analysis

The northern part of the Roya Valley is less terraced than the southern one due to the importance of high-altitude pasture and woods [54]. This difference is also due to the density of population during the 19th century, which is correlated with the percentage of terraced plots (r = 0.86), because highly populated municipalities need more food and have a larger labor force to build and maintain terraces. Most of the northern population were shepherds and migrated to the Riviera during the winter to feed their herd [41,54,55]. The orientation of the economy interacting with the density of population brings about another example of the importance of these socio-economic factors in the spatial organization of a territory contrary to a deterministic vision [40].

The diversity of land use during the 19th century suggests an economy partly based on auto-consumption (vine, cereals) and partly based on formal or informal markets (olive, breeding, hay) [43]. Intercrops, which characterize Mediterranean agro-systems [23], are noticeable in southern municipalities. Compared with the description of Mediterranean and mountain economies [56], land use was more diversified in the southern municipalities than in the Mediterranean territories, including pasture for breeding activity, and the northern municipalities were even more specialized in breeding activity [42–44]. While in southern municipalities, the economy of the terraced plots was based on olive oil, cereals, etc. in the northern municipalities, terraced plots were partly occupied by pasture, contributing to hay production for the livestock [43,44]. During the 21st century, abandoned and cropped terraced land does not depend on altitude or distance to the valley and villages, contrary to previous studies [21], including those in southern villages, where there is a significant persistence or renaissance of olive-growing, as observed at a regional scale, due to professional or hobby farmers [22,59]. Access by car is now decisive.

4.4. Resilience of Historical Landscapes

Our hypothesis of the resilience of historical landscapes is validated by our study, following "contemporary definitions considering resilience to consist of (1) the amount of disturbance that a system can absorb while still remaining within the same state or domain of attraction; (2) the degree to which the system is capable of self-organization (versus lack of organization or organization forced by external factors); and (3) the degree to which the system can build and increase its capacity for learning and adaptation" [5]. Meanwhile, almost all the processes that characterize the resilience of traditional landscapes are represented in our study [3,6]: abandonment, renaissance, continuity, etc.

First, a high number of terraces persist (continuity), despite the amount of disturbance since the 19th century (abandonment, demographic loss, Storm Alex) [5]. We observe hardly any degradation of dry-stone walls in abandoned terraces with the Lidar data, contrariwise to other studies [2,10,17–19]; this finding should be verified by field work ([20], Story team, Tterrcat project, https://projetstory.wordpress.com/actualites/, accessed on 30 March 2024).

Second, co-variations between the surfaces of cropped terraces and the population (more recently the number of farmers) suggest the self-organization of the socio-ecological system [5]. The legacy of terraces has been built in a tough historical context, characterized by military conflicts [41,42], fluctuating demographics [cassini.ehess.fr], extreme events until the end of the 19th century [8,9,43,44], and the changing economy since the end of the Second World War [25,26] or even before (after the First World War in the Maritime Alps, [45]). Terraced plots covered with cereals and pasture that no longer correspond to the needs of food supply and modern breeding activity almost disappeared, similar to in other regions [2,3,6,25,26,32].

Third, the continuity of cropped terraces since the 17th–18th century suggests a "persistence despite the amount of disturbance" [5]. This legacy is maintained particularly in some ancient terraces that are still cropped with olive and chestnut trees, as observed in other studies [3,6,45]. This is due to the longevity of these trees, the insignificant damages suffered by olive groves in Sospel and Breil during the freeze event in 1956 and the small labor force required to obtain a harvest, whether sold or self-consumed, fitting with the requirements of hobby and professional farmers [22,59].

Fourth, the renaissance of olive growing observed in the Roya Valley, as in other regions [3,6,22], suggests a "capacity for learning and adaptation" [5]. It is less pronounced than the doubling of the number of trees observed between 1956 and 2011 in France, but part of this difference is due to the lack of frost damage in the Roya Valley in 1956 [23]. This renaissance is still ongoing after the extreme events that hit the Roya Valley based on the strong participation of local communities [2,60] (olive growing: Cultures en terrasses, https://www.terrassesroya.eu/; vineyards in La Brigue (https://miimosa.com/fr/projects/la-ciappea-renaissance-de-la-viticulture-en-haute-roya; chestnut woods in Tende (https://www.chataigne-roya.fr/).

Finally, the resilience of this historical landscape relies on the adaptation capacity of the local population itself. First, despite fluctuations, the demography recovered after the military conflicts between France and Italy. What could have led to the total collapse and depopulation of this valley has forged a cross-border culture. This cross-border culture is superimposed with differences between Piedmont's culture to the north and Liguria's culture to the south. Second, Storm Alex in October 2020, which could have led to the collapse of the territory, triggered a strong social response and solidarity. The legacy of terraces is mostly invisible though important culturally and ecologically for the resilience of this valley.

4.5. Limits and Prospects of Our Study

It is important to bear in mind that the accuracy of the results obtained depends on the reliability of the materials and methods (Table 1). Differences in interpretation, variations in mapping methods and other variables may lead to uncertainties in our results. Consequently, the results of this analysis are specific to the protocol adopted and may not correspond perfectly to the reality on the ground. These uncertainties could be reduced by using other maps and cadasters drawn up during the 18th century (Turin archives, in progress). A dating campaign is required [33], using innovative methods for the terraces [61] and the remains of the huts built next to the terraces. Orchard surfaces mapped by the BD TOPO IGN should be verified with recent aerial photography and field surveys. The acceleration of the increase in forested surfaces between 1990 and 2018 [52] suggests that more frequent dates should be considered, similar to previous studies [23,25]. This sensitivity to data must be kept in mind when considering the results and to recognize the inherent limitations of using historical data in landscape studies.

As the Roya Valley is a cross-border territory, it is important to widen this study to the whole catchment, including the mouth of the river in Italy. In the Italian, southern part of the catchment (municipalities of Olivetta, Airole and Ventimiglia), terrace mapping is still in progress. Partial information is available on forests (Period 1897–2023), scrubland, vine, olive and crops (Period 1950–2023). If we consider both Italian and French parts of the valley, the forest cover multiplied by two between the 19th century and the 1950s, and once more since then, similar to other Mediterranean mountain territories [26]. In total, forest cover has been multiplied by four (Le Vot, unpublished master thesis), a higher increase than that observed in the whole Provence–Côte d'Azur region (excluding the County of Nice) during a longer period (18th–21st century, *3.5) [30].

Scrubland was not mentioned during the 19th century and was probably lacking or merged with pasture [45]. According to the digitized SCAN Historique 1950 (https://geoservices.ign.fr/scanhisto, accessed on 1 April 2023), scrubland covered 6.2% of the surface of the French part of the catchment and less than 0.1% of the Italian part. Agricultural activity was maintained better in the Italian municipalities, for a diversity of crops, depending on the market, including flowers, market gardening; 52% of olive groves were still cropped in 2006 [https://srvcarto.regione.liguria.it/geoviewer2/pages/apps/geoportale/index.html?id=680, accessed on 1 April 2023].

5. Conclusions

This study, based on multi-source data, has mapped the extension of terraced land and reconstructed their land-use trajectories in a Mediterranean mountain valley. By comparing the land use of the terraces since the 17th century with demographic data, the literature and local community testimonies, the resilience of terraced landscapes has been based on the ability of local populations to overcome human and natural hazards through the past 5 centuries. Today, these historical landscapes have largely been swallowed up by the reclaiming forest, but they persist in the ground and represent potential for the future in a post-disaster context.

Our methodology and results could be applied in other Mediterranean mountain valleys facing the same problems and able to rely on the heritage of historical landscapes and the potential participation of local communities. Valleys similar to Roya, arranged all around the Mediterranean Basin and flowing into the sea, are subject to land abandonment and increasingly frequent and violent extreme events as a result of climate change. This configuration leads to high vulnerability to climate change, with coastal erosion problems combining with those linked to devastating floods coming from upstream. The resilience of historical landscapes constitutes, in this context, an asset, providing a nature-based solution to face the challenges and uncertainties of the present and the future. This kind of study should also give useful information to local communities to assess the capacities of terraced plots and, more generally, historical landscapes to be rehabilitated for the revitalization of the territory (Story team, Tterrcat project, https://projetstory.wordpress.com/actualites/, accessed on 30 March 2024).

The transposition of our methodology will be tested in the future at the mouth of the Roya watershed, located in Italy. The cross-border context, a major difficulty in the Roya valley, does not arise in all Mediterranean mountain valleys, which should facilitate the transfer of this method. In European countries, historical sources, dating from at least since the 19th century, are available on-line. Lidar data are currently available, and automatized methods would allow us to extend this kind of study, as is already the case in the whole of Italy. The results obtained in the Roya catchment make it a “sentinel territory” for socio-ecological and historical landscape resilience and an example of the kind of resilience that can be achieved in the future. The citation of Marc Antrop [28], “Landscapes of the past are important for the future”, is increasingly true in a changing world.

Supplementary Materials: The following supporting information can be downloaded via this link: https://www.mdpi.com/article/10.3390/land13050592/s1, Table S1: Populations of the main municipalities of the Roya Valley 1793–2017, Table S2: Economy of the County of Nice and the municipalities of Tende and La Brigue in the 19th century [43], Table S3: Economy of the Roya Valley in the 19th century [43,44,54], Table S4: Land-use change in the Maritime Alps in 1896–1929 [45], Figure S1: Detection of terraces and land use with different sources.

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