

## Research Paper

# Land-use legacy drives post-abandonment forest structure and understory in the western Alps

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## HIGHLIGHTS

- Forest expansion is the main land-use transition in a landscape of the western Alps.
- Legacy of grasslands and wooded areas affect post-abandonment forests differently.
- Post-abandonment forest overstory and understory depends on historical land-use.
- Land-use legacy is a key factor for understanding post-abandonment forest landscapes.

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## ABSTRACT

Rural exodus from European mountain regions to lowlands has triggered natural reforestation of abandoned lands in the 19<sup>th</sup> and 20<sup>th</sup> centuries, altering the provision of ecosystem services and creating management challenges. Post-abandonment forests are complex ecosystems that respond over time and space to several drivers. Their management requires integrated approaches that involve insights from historical ecology. Our study aimed to assess the influences of the land-use legacies on post-abandonment forest overstory and understory and provide insights on suitable management strategies. We assessed these influences using multiple scales (from landscape to field scale) and ecological approaches (vegetation, forest, and landscape ecology).

We identified post-abandonment forests within a western Alps watershed through a land-use/land-cover change detection from 1954 to 2017. Field surveys were conducted in three different land-use legacy types (i. e., transitions from former grasslands, wood-pastures, and sparse forests to dense forests) to analyse forest overstory and understory. We explored the influences of land-use legacy on post-abandonment forests through redundancy analysis, using forest overstory and understory variables as response variables and environmental factors as predictors. Our study revealed successional and environmental differences among post-abandonment forests, notably depending on the historical presence of biological legacies: forests originating from former wooded areas exhibited ecological conditions closer to natural trajectories, while those resulting from abandoned grasslands still express conditions similar to the pre-abandonment ones. Based on our findings, we discuss how the direct implications of land-use legacies on post-abandonment forests can provide insights into their management.

## 1. Introduction

Over millennia, human activity has been a driving force shaping landscapes, influencing ecological processes, and the provision of

ecosystem services (Ellis, 2015). In European mountain regions, centuries of interaction between natural and anthropic dynamics have shaped semi-natural agro-silvo-pastoral ecosystems (Naveh, 1995). Traditional management practices, including silviculture and grazing,

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fostered the development of this complex cultural landscape mosaic, dominated by an interspersed of forests, wood-pastures, grasslands, and croplands (Garbarino & Weisberg, 2020; Gellrich et al., 2007; MacDonald et al., 2000). These cultural landscapes act as biodiversity hotspots because their heterogeneous composition and configuration create a multitude of ecological niches (Tasser et al., 2024; Van der Sluis et al., 2019). They provide food, shelter, and habitat for several species and serve as enduring evidence of the historical coexistence between humans and nature (Zimmermann et al., 2010). Changes in their landscape character can therefore trigger a cascading effect on ecosystems and human livelihoods (Dieterich & Van Der Straaten, 2004).

Industrialisation and socio-economic changes led to an intense abandonment of agricultural land and rural exodus from the end of the 19th century, which peaked after World War II (Batzing et al., 1996; Pereira et al., 2010). This dynamic engendered profound transformation in land-cover and land-use patterns throughout Europe (Anselmetto et al., 2024; Bicudo da Silva et al., 2020; Plieninger et al., 2016), especially in the alpine regions (Batzing et al., 1996; Garbarino et al., 2020; MacDonald et al., 2000). A prevailing trend involves the polarisation between forest expansion in marginal areas and increased human pressure on lowland plains and valley bottoms (MacDonald et al., 2000; Van der Sluis et al., 2019). Below the forest line, secondary succession in abandoned open and semi-open areas such as croplands, meadows, grasslands and wood-pastures resulted in dense forests or thickets (Anselmetto et al., 2024; Falcucci et al., 2007; Garbarino et al., 2020). These changes threaten the existence of semi-natural agro-silvo-pastoral landscapes and affect their provision of ecosystem services (Van der Sluis et al., 2019). Indeed, post-abandonment natural reforestation alters the biogeochemical cycle, offsets the deforestation process on the global scale (Lasanta et al., 2015), and reduces landscape complexity promoting wildfire size and severity (Mantero et al., 2020). Moreover, natural colonisation increases biodiversity in the early stages of secondary succession (Höchtel et al., 2005) due to the development of a mixture of open areas and dense vegetation and the establishment of fringe species (Lasanta et al., 2015; Zarovali et al., 2007), but decreases over the mid-long term, particularly due to the loss of species associated with low-severity continuous disturbances typical of forest edges and open habitats (Fontana et al., 2014; Laiolo et al., 2004; Marini et al., 2007). It is crucial to note that the detected implications and their interpretation depend on several factors, including the scale of observation, socio-economic history and legacy, the perception of landscape value by distinct social groups, and established conservation goals (Conti & Fagarazzi, 2004; Höchtel et al., 2005; Sitzia et al., 2010).

Natural reforestation processes on agricultural land are complex dynamics driven by the synergistic effects of multiple socio-ecological factors (Garbarino et al., 2020; Pedersen et al., 2023). This is particularly pronounced on post-abandonment lands, where factors such as a dense herbaceous layer, the type and level of fertilisation, and grazing pressure can introduce delays in shrubs and trees encroachment (Rebele, 2013). Furthermore, the colonisation process is strongly influenced by time since land abandonment, topographic features, soil properties, and the type and proximity of nearby forest and shrub areas (Garbarino et al., 2020; Holl et al., 2018; Pedersen et al., 2023). Notably, biological legacies (e.g., scattered trees) serve as seed sources for reforestation and contribute to a canopy closure dynamic (Hughes et al., 2023; Manning et al., 2006; Meli et al., 2017), while the accumulation of stones resulting from meadow clearing (e.g., to prevent scythe damage), the presence of artefacts (e.g., dry stone walls and terraces) and former cattle trampling create microhabitats conducive to the establishment of seedlings (Venturi et al., 2022). These land-use legacies play a pivotal role in shaping the configuration, composition, and provision of ecosystem services within post-abandonment forest landscapes, thus influencing and constraining the trajectories of future ecological processes.

Historical ecology, i.e., the study of natural changes over time, with a particular focus on human-environment interactions (Beller et al.,

2017), stresses the significant impact of historical land-use on post-abandonment landscapes (Rhemtulla & Mladenoff, 2007). Understanding these effects is essential to understand current ecological processes and implement rational and sustainable practices (Armstrong et al., 2017; Beller et al., 2017; Bürgi et al., 2017). However, it is challenging due to the complex interaction of several colonisation drivers over time and space, especially for forest understory vegetation, which responds most directly and rapidly to changes in overstory structure and composition (Landuyt et al., 2019). Therefore, the management of post-abandonment forests requires integrating the perspective of several ecological approaches with the analysis of land-use legacy (Garbarino & Weisberg, 2020). Although land-use change has been widely monitored in post-abandonment forests, studies that integrate remote sensing approaches with field surveys for the analysis of the implications of the land-use legacy on these ecosystems remain relatively scarce. Furthermore, this traditional assessment focuses on the forest overstory (i.e., tree layer), often neglecting the functional role of the forest understory (i.e., herbaceous layer) and its implications for landscape planning.

In this study, our aim is to explore the influences of land-use legacy (i.e., former land-use/land-cover) on post-abandonment forests overstory and understory in a watershed of the Alps through remote sensing and field surveys. To achieve this, we implemented a multiscale approach which allows us to detect dynamics that might be hidden at a single scale of observation: (I) at the landscape scale we evaluated land-use/land-cover (LULC) changes of a montane landscape in the Alps over a sixty-year period; (II) at the watershed scale we identified the land-use legacies and the post-abandonment forests; (III) at the field scale we surveyed a sample of post-abandonment forests to explore the influence of land-use legacy on forest overstory and understory. From our results, we discuss the implications of land-use legacy assessment in managing and planning post-abandonment forest landscapes. This study integrates landscape ecology with forest ecology (i.e., dendrometry) and vegetation ecology (i.e., phytosociology), since the composition of the forest understory serves as a valuable indicator of persistent imprints resulting from changes in LULC and facilitates the assessment of the successional dynamics (Landuyt et al., 2019).

## 2. Materials and methods

### 2.1. Study area

We evaluated the LULC changes at the landscape scale, which consists of a limited part of the lower Pesio Valley (44°16' N, 7°40'E) in the Italian Ligurian Alps (Fig. 1). The study area is partially included in the Regional Park 'Parco Naturale del Marguareis' and the EU Natura 2000 network site 'Alte Valli Pesio e Tanaro' (IT1160057). It covers 1600 ha and its elevation ranges between 653 and 1586 m a.s.l. The climate is cold temperate (*sensu* Bagnouls-Gausson classification), with a mean annual temperature of 7.3° C and an average annual precipitation of 1394 mm year<sup>-1</sup>. Precipitation peaks occur in spring (30 % of the average annual precipitation) and autumn (26 %). The forests are dominated by *Castanea sativa* Mill. (77 %) below 1200 m a.s.l. and by *Fagus sylvatica* L. (20 %) in the upper belt of the landscape. In this region, the natural potential vegetation of forest ecosystems consists in *Fagus sylvatica* and *Abies alba* Mill. stands.

We analysed land-use legacy influences on post-abandonment forests at the watershed scale in the Fiolera catchment (44°16'23"N, 7°40'36"E), a lateral valley with a west-east orographic orientation, located inside the area used for landscape analyses, and extended over 300 ha from 751 to 1586 m a.s.l (Fig. 1).

### 2.2. Land-use history

Land-use in the study area has changed over millennia due to human pressure, and current forest and grassland patterns are strongly related to historical management. The arrival of Carthusian monks in the Pesio

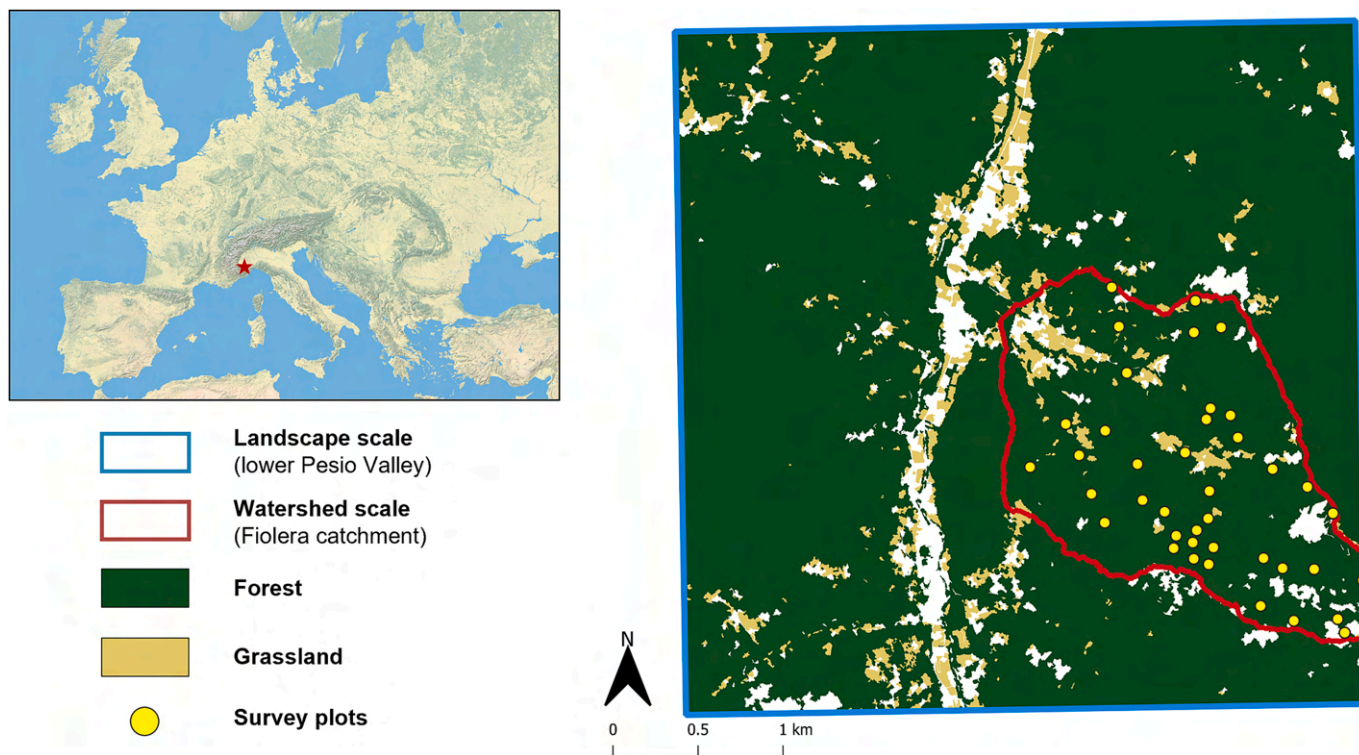


Fig. 1. Study areas at the landscape and watershed scales showing forest and grassland current cover and location of the plots where post-abandonment forests were surveyed. Basemap powered by ESRI, ESRI terrain.

Valley in 1173 CE was a significant milestone in the history of the landscape. They shaped the social and cultural template of the area by integrating novel agricultural and silvicultural systems (Motta & Garbarino, 2003). At lower elevations, they cultivated *Castanea sativa* for fruit production. In the mountain belt, they favoured the coppicing of *Fagus sylvatica* for firewood, while at higher elevations, *Abies alba* was favoured and planted for exploitation as round timber (Motta & Garbarino, 2003). Historical records show that *Fagus sylvatica* was typically subjected to clear cutting with rotation cycles of approximately 80 years. However, since the twentieth century, it has been managed as a coppice with rotations of about 20–30 years, along with low-elevation *Castanea sativa* forests, which were coppiced due to the spread of diseases (Motta & Garbarino, 2003). The peak of forest exploitation in the valley probably occurred between 1760 and 1854, when the Royal Glass and Crystal Factory was operating in the Chiusa di Pesio municipality. In addition to fuelwood and logs, the production of wood charcoal was notably widespread and organised and continued until World War II (Motta & Garbarino, 2003). Forest exploitation underwent strict regulation from the late 1970s when the Regional Park was established (Piedmont Regional Law No. 84, 1978).

Livestock grazing historically contributed to the creation and maintenance of pasture patches enclosed by a forest matrix, particularly below the upper elevation range of *Fagus sylvatica* species distribution (approximately 1500 m a.s.l., Garbarino et al., 2014). The small size of these lower-altitude pastures represented an economic constraint to their use, leading to their gradual abandonment. Indeed, both human population and cultivated land decreased in the last decades (–19 % of population between 1951 and 2020, and –37 % of cultivated land between 1970 and 2010) (data from ISTAT). In particular, the decline of seasonal grazing in the second half of the 20th century led to a contraction in the overall surface area of pasture patches and an increase in the dimension of the forest matrix. This succession caused complete closure of smaller pasture patches and fragmentation of the largest ones, increasing their number, and creating wider ecotonal areas composed mainly of species different from those of the surrounding forests

(Garbarino et al., 2014).

### 2.3. Landscape changes

We assessed the changes in LULC between 1954 and 2017 at the landscape scale through historical aerial photographs and recent satellite images (Table 1). We georeferenced and orthorectified historical aerial photographs at 0.5 m resolution using the PCI Geomatica software. We segmented the resulting ortho mosaics using an automated object-oriented methodology through eCognition software (scale factor 100, color factor 0.5) (Garbarino et al., 2014; 2020). A minimum mapping unit of 100 m<sup>2</sup> was fixed to create the polygons. We classified all polygons in a GIS environment through visual photointerpretation into seven LULC classes: dense forest (tree cover > 80 %), sparse forest (tree cover between 40 % and 79 %), wood-pasture (tree cover between 10 and 39 %), grassland (tree cover < 9 %), cropland, urban (streets and buildings), and unvegetated (residual category that includes bare soil, water, and rocks). Accuracy assessment of each LULC map was performed by the same operator through a new visual photointerpretation of an independent testing set of 110 randomly selected polygons (Congalton, 1991). The overall accuracy of the LULC maps of 1954 and 2017 was 92 % and 97 %, and the k statistic (Carletta, 1996) was 90 %

**Table 1**  
Main features of photographs used for LULC analysis.

	Year	
	1954	2017
Flight	GAI	Google
Reference	IGMI	Google Earth
Type of flight	Plane	Satellite
Date of acquisition	July 1954	August 2017
Film	Panchromatic B/N	Colour panchromatic
Focal length	153	–
Average flight height	7500	–

and 93.5 %, respectively.

We quantified the LULC changes over the 63 years through a transition matrix obtained by comparing the two LULC maps (Appendix A). The transition matrix indicates the surface area that changes among the seven LULC classes. The significance of changes in LULC was assessed using the chi-square test.

#### 2.4. Land-use legacies influences

We defined ‘post-abandonment forests’ as polygons classified as dense forest on the 2017 map and classified as sparse forest, wood-pasture, grassland, or cropland in 1954. We defined ‘land-use legacy’ as the historical LULC classes that resulted in post-abandonment forests. As there were no transitions to dense forest from areas classified as cropland, we identified three different land-use legacies towards dense forest: grassland, sparse forest, and wood-pasture legacies. For subsequent field surveys, we selected 40 post-abandonment forest patches across these three legacies. To achieve a proportioned sample, we selected them based on the surface area occupied by the land-use legacies: 27 patches for former grasslands, 7 patches for former sparse forests, and 6 patches for former wood-pastures. Field surveys were carried out in summer 2021 by four of the authors.

##### 2.4.1. Forest overstory variables

To assess the forest structure, we established in each patch a plot with a radius of 5 or 10 m, depending on the density of the overstory. We collected the species and diameter at breast height (dbh, 1.30 m) of all living and snag seedlings (<1 cm dbh), saplings (1 to 5 cm dbh), and trees (>5 cm dbh). We sampled two increment cores at breast height (1.30 m): one from the largest individual and one from an individual with a representative (i.e., mode) diameter for the plot, regardless of species.

We described the forest structure through classic dendrometric attributes such as: individuals per hectare, basal area per hectare, and the maximum and mode age for each plot. We then grouped the overstory species into ‘late successional’ (species of the natural potential vegetation) or ‘pioneer’ (Appendix B). Moreover, we assessed forest overstory diversity by calculating for each plot two Brillouin diversity index for both structure (i.e., the number of individuals per diameter class; with class size of 1 cm) and species composition, according to the following formula:

$$\text{Brillouin index} : HB = \frac{\ln(n!) - \sum_i^n \ln(n_i!)}{n}$$

where HB indicates the Brillouin index,  $n_i$  is the number of observations from the sample in the  $i^{\text{th}}$  of  $m$  categories (species/diameter classes) and  $n$  is the total number of individuals. We chose the Brillouin index because it emphasises species richness and is more suitable in the case of samples drawn for small populations (Pielou, 1966).

##### 2.4.2. Forest understory variables

To assess the composition of the forest understory, we established a plot with a radius of 3 m. We visually assessed the relative abundance (i.e., percentage of ground cover) of all vascular plant species, including shrub, tree seedling and sapling, below 1.30 m. We limited our vegetation surveys to species with relative abundance (SRA) in the plot  $\geq 1$  %. We described the average ecological conditions of the understory using the following species-based indicators described by Landolt et al. (2010), each weighted by its SRA in the plot: nutrient value (N), indicating the nutrient content of the soil (referring mostly to nitrogen and often to phosphorus); humus value (H), indicating the humus content (i.e. the amount of dead organic material in or on the soil); light value (L), indicating the average amount of light received by a species in its habitat. Landolt’s indicators (range between 1 and 5) aim to characterise the niche of the plant in natural communities, describing its

physiological growth limits and competitiveness abilities (Landolt et al., 2010).

To understand plant community shifts due to management changes, we grouped understory species into Social Behaviour Types (SBTs) (Borhidi, 1995), defining each group on a phytosociological basis in accordance with Troiani et al. (2016). To group species into SBTs, we classified each species to its phytosociological optimum at the class level, as identified by Aeschmann et al. (2004); then, we pooled species belonging to different phytosociological classes into the following SBTs according to a successional dynamic: RUDERAL (typical ruderal species; associated with the phytosociological class of *Artemisietea vulgaris*), GRASS (typical grassland species; *Festuco-Brometea*, *Juncetea trifidi*, *Molinio-Arrhenatheretea* classes), MEGAFORB (typical megaforb species; *Filipendulo-Convolvuletea*, *Mulgedio-Aconitetea* classes), SHRUB (typical shrubland and fringe communities species; *Crataego-Prunetea*, *Trifolio-Geranietea* classes), WOOD (typical woodland species; *Carpino-Fagetea*, *Quercetea pubescentis*, *Quercetea robori-sessiliflorae*, *Robinietea*, *Vaccinio-Piceetea excelsae* classes) (Appendix C).

To evaluate the productivity and suitability of the understory for grazing, we computed the pastoral value (PV) (Pittarello et al., 2020). PV is a synthetic index derived from botanical composition to express forage productivity, quality, and palatability for livestock (Daget & Poissonet, 1969). To compute PV, we attributed an Index of Specific Quality (ISQ) to each understory species according to its productivity, morphology, structure, palatability, and preference by livestock (ISQ database available in Pittarello et al., 2024). The ISQ ranged from 0 (low quality species) to 5 (high quality species) (Daget & Poissonet, 1971). PV, which ranges from 0 (null) to 100 (high), was computed according to the formula of Daget & Poissonet (1969):

$$PV = \sum_{i=1}^n (SRA_i \times ISQ_i) \cdot 0.2$$

where  $ISQ_i$  is the ISQ value for the species  $i$  and  $SRA$  is the species’ relative abundance.

##### 2.4.3. Environmental factors

We derived topographic and anthropogenic factors for each plot. We used a 5-m spatial resolution digital terrain model (DTM) from the Piedmont Region (Regione Piemonte, 2019) to calculate elevation, slope, and heat load index (HLI). The HLI indicates the incident solar radiation according to the aspect and provides information about the ground surface temperature (McCune & Keon, 2002). Anthropogenic variables were derived from open street maps and included the Euclidean distance from buildings and roads. Spatial analyses were carried out with QGIS 3.22.14 and SAGA 7.8.2 softwares (see Appendix D for descriptive statistics of the calculated variables).

##### 2.4.4. Statistical analysis

We evaluated the influences of land-use legacy on post-abandonment forests using a multivariate constrained ordination approach. We created a model to explore the variability among post-abandonment forests originating from the three land-use legacies. We used forest overstory (maximum and mode age, basal area of pioneer and late successional living and dead individuals, Brillouin index of overstory species and structure) and understory variables (SBTs, Landolt indicators H-L-N and PV) as response variables and environmental factors as predictors (Table 2). The results of a preliminary Detrended Correspondence Analysis (DCA; Hill & Gauch, 1980) on the response variables indicated a homogeneous data set (length of DCA first axis < 3 SD) for which linear ordination methods are suitable (Lepš & Šmilauer, 2003). For this reason, we performed a redundancy analysis (RDA). We assessed the significance of the RDA using Monte Carlo permutation tests with 999 iterations, and the significance test of the RDA axes was adjusted using Holm correction. For the RDA diagram, we used plots grouped into land-use legacy and assessed their significant differences through a non-parametric multi-response permutation procedure

**Table 2**

Variable included in the RDA, divided by category. Forest overstory and understory variables were used as response variables while environmental factors were used as predictors.

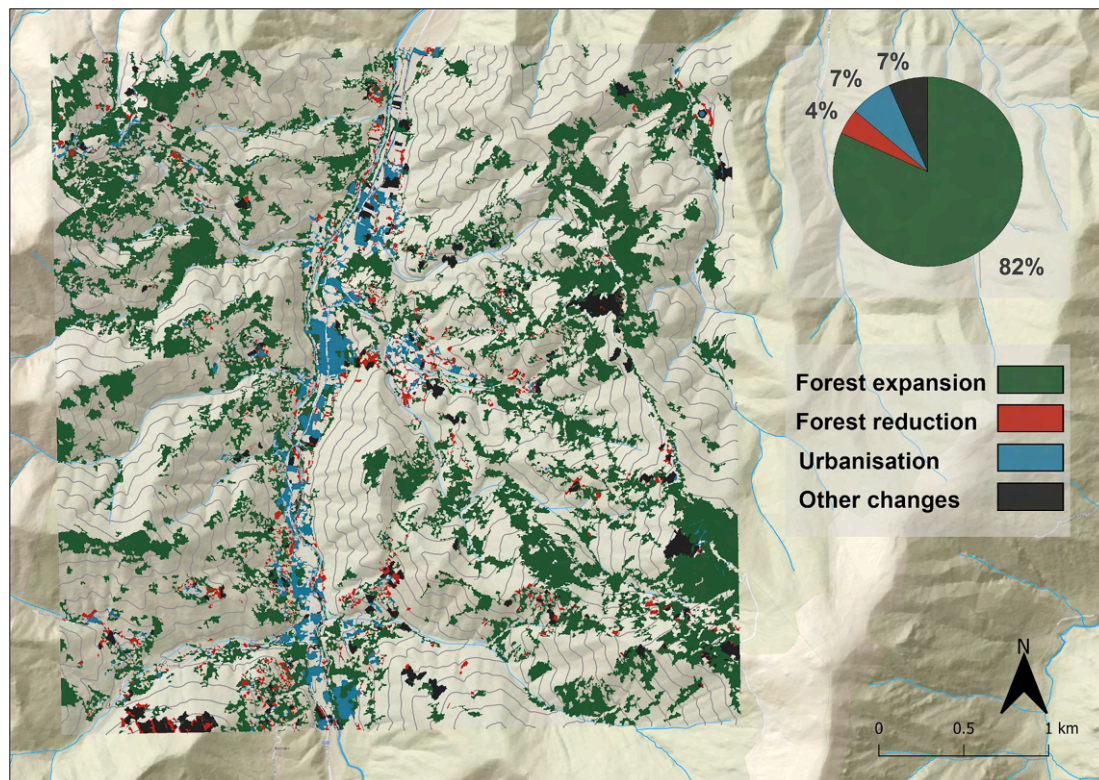
Category	Variable	Description	Unit	Sampling
<b>Forest overstory</b>	MaximumAge	Age of individual with larger dbh	y	10–5 m
	ModeAge	Age of individual with more frequent dbh (i.e., mode)	y	10–5 m
	LivePioneer	Basal area of living pioneer individuals	m <sup>2</sup> ha <sup>-1</sup>	10–5 m
	LiveLateSuccessional	Basal area of living late successional individuals	m <sup>2</sup> ha <sup>-1</sup>	10–5 m
	SnagPioneer	Basal area of pioneer snag individuals	m <sup>2</sup> ha <sup>-1</sup>	10–5 m
	SnagLateSuccessional	Basal area of late successional snag individuals	m <sup>2</sup> ha <sup>-1</sup>	10–5 m
	OverstoryStructureDiversity	Brillouin index for forest overstory structure	–	10–5 m
	OverstorySpeciesDiversity	Brillouin index for forest overstory species composition	–	10–5 m
	<b>Forest understory</b>	L	Landolt's light value	Factor
N		Landolt's nutrient value	Factor	3 m
H		Landolt's humus value	Factor	3 m
RUDERAL		Relative abundance of species typical of ruderal conditions	%	3 m
GRASS		Relative abundance of species typical of grassland conditions	%	3 m
MEGAFORB		Relative abundance of species typical of megaforbs conditions	%	3 m
SHRUB		Relative abundance of species typical of shrub conditions	%	3 m
WOOD		Relative abundance of species typical of woodland conditions	%	3 m
PV		Pastoral Value	–	3 m
<b>Environmental factor</b>		Elevation	Average plot elevation	m
	Slope	Average plot slope	°	DEM 5 m
	HLI	Average Heat Load Index of the plot	–	DEM 5 m
	RoadDistance	Euclidean distance from roads	m	OSM
	BuildingDistance	Euclidean distance from buildings	m	OSM

(MRPP; Mielke, 1991) with Bray–Curtis distances. MRPP tests whether there is a significant difference between two or more groups of sample units based on the weighted mean distances among sample units within each group. The MRPP does not require distributional assumptions and is suitable for unbalanced groups. For statistical analyses, we used R v.4.3.2 and the vegan package v.2.6-4 (Oksanen et al., 2022). Data visualisation was performed using the packages ggplot2 v.3.4.2 (Wickham, 2016) and circlize v.0.4.15 (Gu et al., 2014).

### 3. Results

#### 3.1. Landscape changes

During the study period, 29 % (470 ha) of the landscape (i.e., lower Pesio Valley) experienced changes in LULC (Chi-square:  $p < 0.001$ ). Forest expansion was the most important dynamic, accounting for 82 % of the total changed area, while urbanisation and forest reduction accounted for 7 % and 4 %, respectively (Fig. 2).



**Fig. 2.** Land-use changes at the landscape scale (lower Pesio Valley). Transitions from one land-use/land-cover class to another were grouped into four dynamics: forest expansion (transitions to forest), forest reduction (transitions from forest), urbanisation (transition to urban areas), and other changes. Basemap powered by ESRI, ESRI standard.

In 1954 and 2017, dense forests and grasslands were the dominant classes of LULC in the lower Pesio Valley (Fig. 3), but while the former increased, grasslands decreased and concentrated mainly at the bottom of the valley. The expansion of dense forests and the contraction of grasslands were the most significant trends in terms of occupied area (+29 %, affecting 20.3 % of the study area; -80 %, 19.8 %, respectively). In relative terms, the most significant changes concerned croplands (+1723 %, 0.2 %), followed by urban areas (+88 %, 1.4 %) and wood-pastures (-83 %, 1.1 %), but each change affected a small portion of the total area.

Most of the area transitioned to dense forests derived from former grasslands (293.9 ha, 75 % of the area in 1954) and, to a lesser extent, former sparse forests (41.7 ha, 91 %) and wood-pastures (18.8 ha, 92 %) (Fig. 3c). On the other hand, 96 % of the dense forests identified in 1954 remained unchanged (1051.5 ha). Another relevant transition was urban expansion, which occurred mainly to the detriment of grasslands (25.3 ha, 6 %), especially at the bottom of the valley. Furthermore, the latter remained unchanged at 15 %, accounting for 76 % of the

grasslands in 2017. Finally, vegetation succession occurred also in 67 % of the unvegetated areas classified in 1954, which mainly transformed into dense forests (10 ha, 62 %).

### 3.2. Land-use legacy influences

Post-abandonment forests covered 29 % of the watershed (i.e., the Fiolera catchment), corresponding to 87 ha. Of these, 75 % were classified as grasslands in 1954, while former wood-pasture and sparse forest classes accounted for 13 % and 12 %, respectively (Fig. 4).

In post-abandonment forests, a total of 18 species were recorded in the overstory and 75 in the understory during field surveys (Appendix B, C). *Fagus sylvatica* was the most dominant species in the understory, contributing 40 % of the total basal area. It reached the highest basal area in former wood-pastures (18 m<sup>2</sup>/ha), followed by former sparse forests (12 m<sup>2</sup>/ha) and grasslands (7 m<sup>2</sup>/ha) (Fig. 5a). Other notable contributors to the overstory basal area were *Betula pendula* Roth (16 % of the total basal area), *Acer pseudoplatanus* L. (14 %) and *Fraxinus*

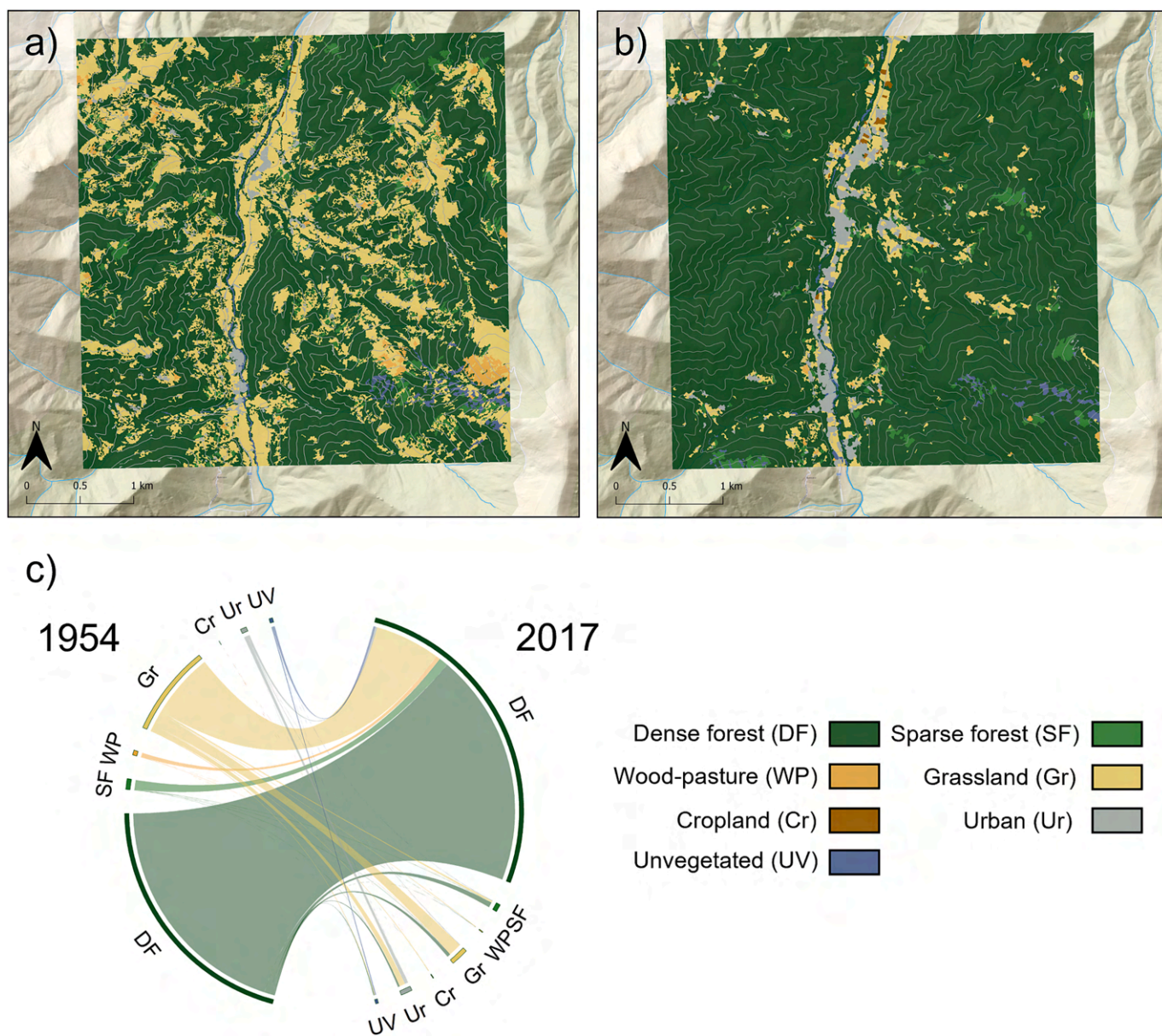


Fig. 3. Land-use/land-cover maps for 1954 (a) and 2017 (b). The chord diagram (c) shows the percentage between land-use/land-cover classes in 1954 (left) and 2017 (right). DF = dense forest, SF = sparse forest, WP = wood-pasture, Gr = grassland, Cr = cropland, Ur = urban, UV = unvegetated. Basemap powered by ESRI, ESRI standard.

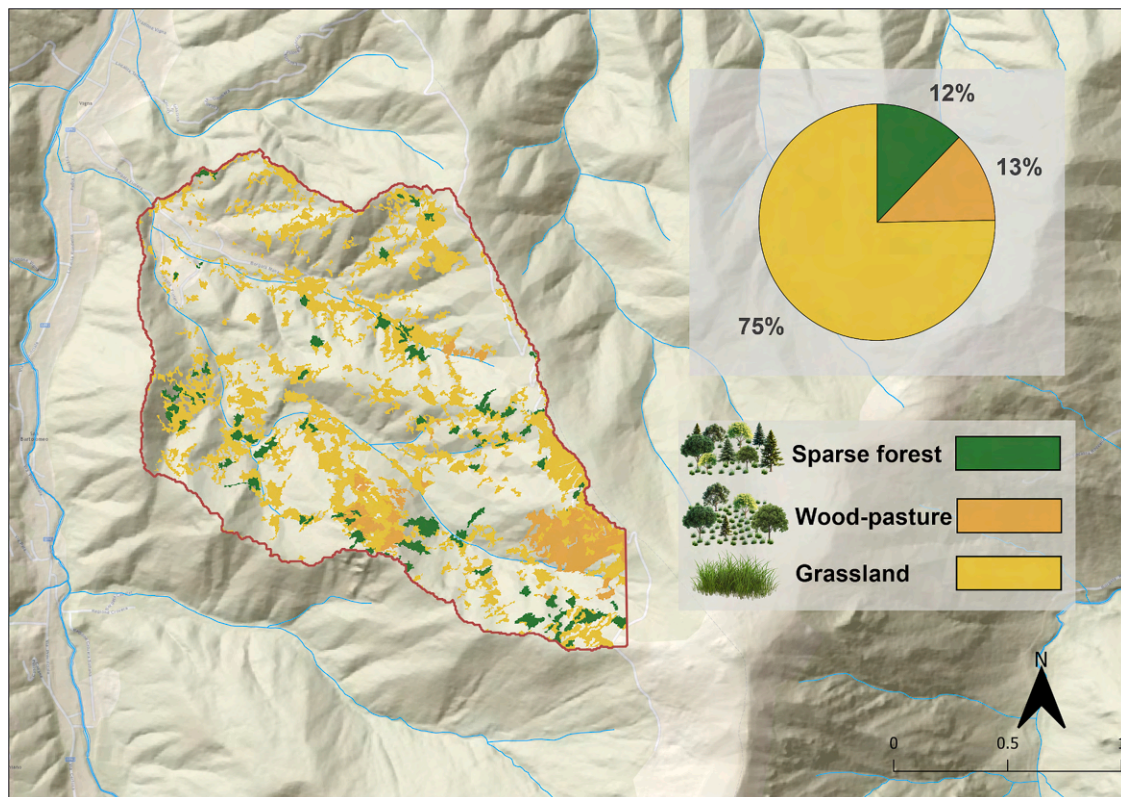


Fig. 4. Map of the post-abandonment forest at watershed scale (Fiolera catchment) classified by land-use legacies. Basemap powered by ESRI, ESRI standard.

*excelsior* L. (12%). In the understory, typical woodland species (WOOD SBT) were the most important in all land-use legacies, contributing 54% of the relative abundance in former grasslands, 88% in former wood-pastures, and 62% in former sparse forests. Typical grassland species (GRASS SBT) were a relevant group in both former grasslands (17%) and sparse forests (23%), while typical shrubland species (SHRUB SBT) were more prominent in former wood-pastures (9%) (Fig. 5b).

The RDA (Fig. 6) explained 30.7% (adjusted  $R^2 = 0.21$ , Monte Carlo permutation tests:  $p = 0.001$ ) of the variation of the post-abandonment forest surveyed in the watershed. The three land-use legacies were significantly different (MRPP:  $p = 0.005$ ) and discriminated primarily along the first constrained axis (23.3% of the variance, Monte Carlo permutation tests with Holm correction:  $p = 0.005$ ), influenced by elevation, distance from buildings, and slope. The basal area of pioneer species in the overstory was positively correlated with overstory species diversity (Brillouin index), which decreased with increasing maximum age. Conversely, the structural diversity of the overstory (Brillouin index) and the presence of late successional species increased with increasing age. These overstories were located in the areas furthest from buildings and roads, at the highest elevations of the watershed and on the steepest slopes, in contrast to the pioneer overstories that were present on the sunniest, flatter slopes and close to human structures (Fig. 4). Similarly, the understory in these areas was characterised by ruderal conditions (RUDERAL SBT) related to human presence and disturbances. Typical grassland species (GRASS SBT) had greater PV and high soil nutrient values (Landolt's N index) and were typical of heliophilous conditions (Landolt's L index). On the contrary, typical woodland species (WOOD SBT) were related to shady conditions, with poor soils and low PV. Lastly, elevation, slope and distance from buildings and roads variables were strongly correlated with each other, caused by the fact that human settlements were mainly located at the bottom of the valley and in flatter areas.

Multivariate analysis sorted post-abandonment forests along the first axis between the three land-use legacies, i.e., former grasslands, spare

forests, and wood-pastures. The forests established on abandoned grasslands were generally located on warmer and gentler slopes, at lower altitudes and closer to buildings and roads. The overstory was dominated by young pioneer stands (live and dead individuals) correlated with high overstory species diversity (Brillouin index). The understory composition was indicative of heliophilous (Landolt's L index) conditions and high nutrient values in the soil (Landolt's N index). It was also correlated with ruderal, shrubland, and grassland conditions (RUDERAL, SHRUB and GRASS SBTs) and with slightly higher PV than other land-use legacies. The WOOD and MEGAFORB SBTs, Landolt's H index, and the diversity of forest structure were negatively correlated. The post-abandonment forests established in the former wood-pastures and sparse forests were placed in proximal positions within the multivariate space. Both are dominated by late successional (live and dead individuals) and older overstory, with typical megaforbs and woodland (MEGAFORB and WOOD SBTs) understory species characterised by lower PV than former grasslands. They were also characterised by lower overstory species diversity and higher structural diversity (Brillouin indices). Landolt's indices described shade conditions (L), high humus (H), and low nutrient content (N). These formations occurred at the higher elevations of the watershed, away from human settlements, and in steep and shaded areas. While forest overstories were similar across these former wooded LULC, small differences emerged in the understory. Specifically, the former wood-pastures showed a higher occurrence of megaforb typical species, higher humus content and shady conditions, and lower nutrient content compared to the former sparse forests.

#### 4. Discussion

In this study, we evaluated how three different land-use legacies (i.e., former grasslands, wood-pastures, and sparse forests) affected post-abandonment forests in a mountain valley of the western Italian Alps. Sixty years were sufficient to modify the landscape structure of a large

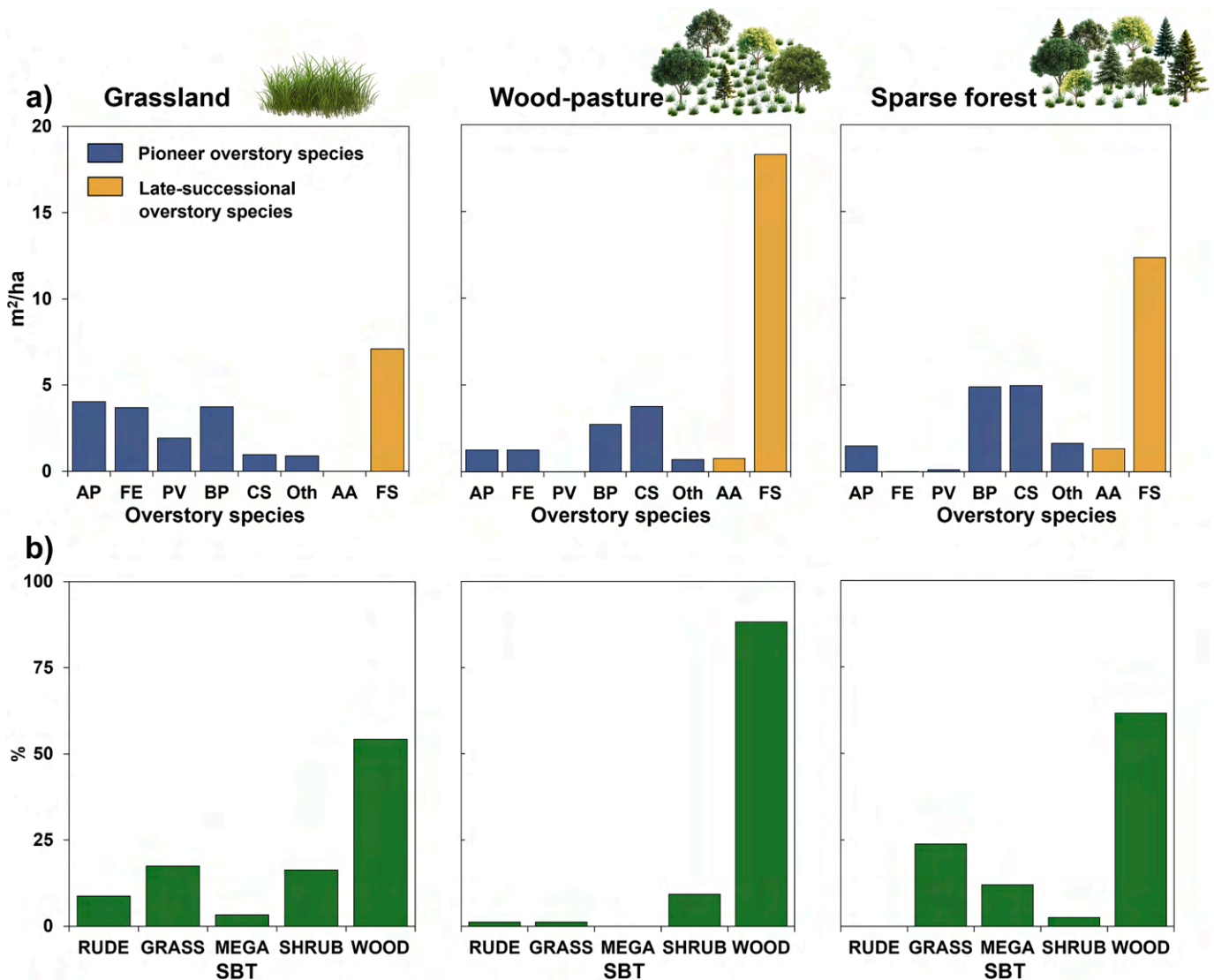


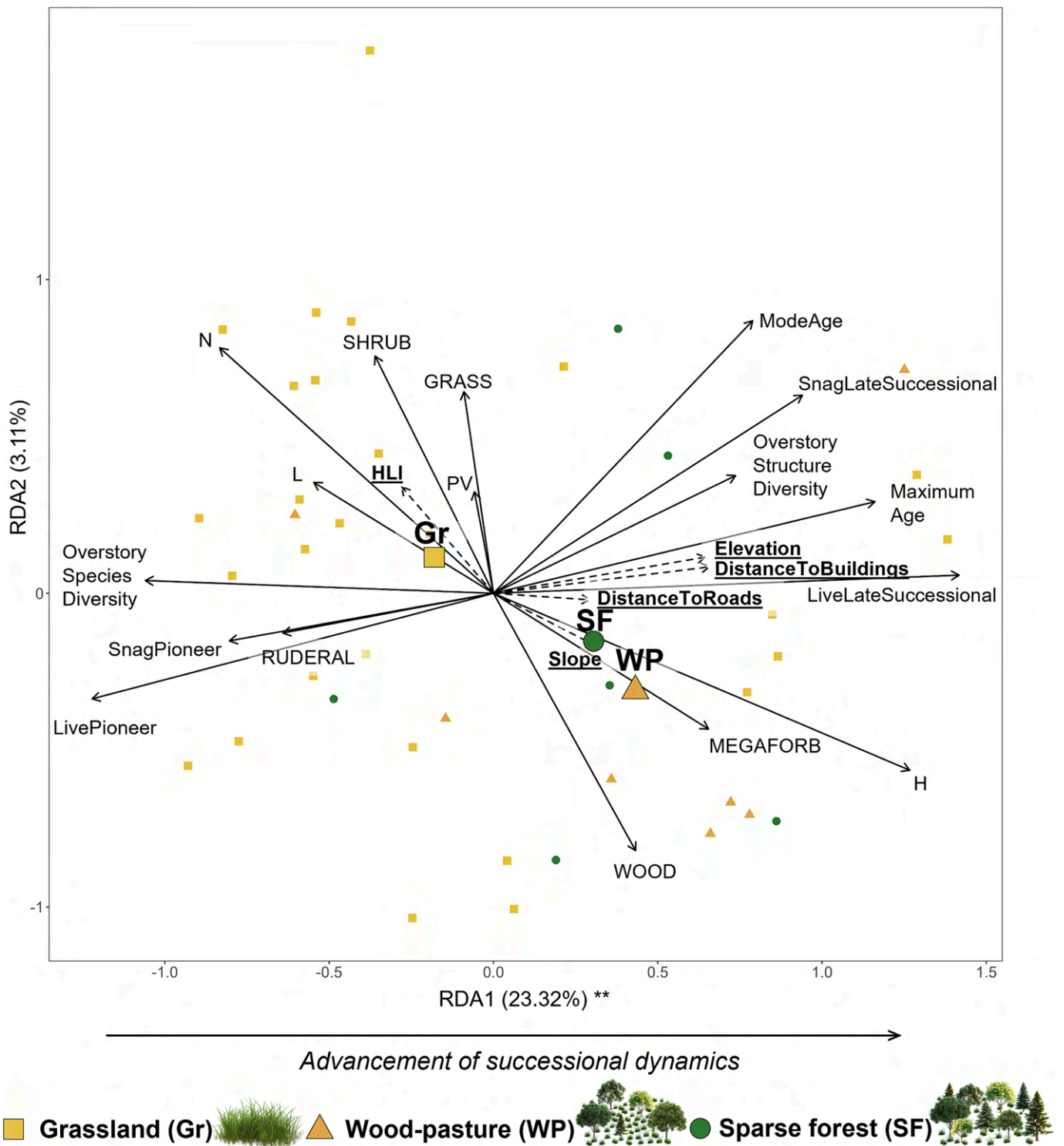
Fig. 5. Contribution to the basal area (a) of the most abundant pioneer (blue) and late-successional (orange) overstory species surveyed and (b) relative abundance of SBT for each land-use legacy. AP = *Acer pseudoplatanus*, FE = *Fraxinus excelsior*, PV = *Prunus avium* L., BP = *Betula pendula*, CS = *Castanea sativa*, Oth = other pioneer species, FS = *Fagus sylvatica*, AA = *Abies alba*. RUDE = typical ruderal species, GRASS = typical grassland species, MEGA = typical megaforb species, SHRUB = typical shrubland species, WOOD = typical woodland species. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

area, changing not only the surface area of different LULC categories, but most importantly the landscape patterns. Post-abandonment forests derived from different land-use legacies exhibited significant successional differences, providing insights for their management and planning.

#### 4.1. Changes in landscape structure

Over the last sixty years, the studied landscape (i.e., lower Pesio Valley) has undergone a strong polarisation between the urbanisation of the valley bottom and the natural recolonisation of marginal montane areas by post-abandonment forest. Natural forest expansion was the main process observed in terms of LULC changes. It occurred due to the abandonment of land and agricultural practices that affected alpine valleys especially since the middle of the last century (Batzing et al., 1996; MacDonald et al., 2000) leading to grasslands reduction mainly in remote and less accessible areas (Marini et al., 2011). Indeed, the forest expanded mainly on marginal and steeper slopes, where abandonment typically occurred earlier due to the difficulty of agro-pastoral

exploitation. The observed dynamics had patterns similar to those that occurred in other European mountain areas (Roura-Pascual et al., 2005; Weisberg et al., 2013) and in other areas of the Pesio Valley (Garbarino et al., 2014; Orlandi et al., 2016). Forest patches increased by 25 % and accounted for 91 % of the total area in 2017, with an annual forest expansion rate of 0.5 % year<sup>-1</sup>. Similar annual increases have been reported in other alpine regions (e.g., +0.6 % year<sup>-1</sup> for the period 1954–2012, Garbarino et al., 2020). Anselmetto et al. (2024) reported an average net rate of +0.64 % year<sup>-1</sup> for the entire Alpine region in the last century. Forest expansion was largely driven by different spatial dynamics of secondary succession: tree encroachment of open areas (grasslands to dense forests) and gap filling in existing forest formations (sparse forests and wood-pastures to dense forests). This expansion reduced the landscape heterogeneity and marginalised other LULC classes, such as grasslands, sparse forests, and wood-pastures, which are now relegated to enclosed patches within the dense forest matrix. These dynamics led to the establishment of post-abandonment forests, which now occur in 23 % of the whole landscape. Besides forests, the polarisation of human pressure followed the trend of population changes,



**Fig. 6.** RDA triplot ordination diagram among forest overstory and understory variables (solid arrows) and environmental variables (dashed arrows, bold underlined label). Survey plots are classified by land-use legacy: Gr – grassland (yellow square), WP – wood-pasture (orange triangle), SF – sparse forest (green circle). Larger shapes indicate land-use legacies centroids. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

which strongly decreased in the higher and remote interior areas and increased in the flat and more accessible areas of the valley bottom (Batzing et al., 1996). Similar processes occurred throughout the alpine regions (Garbarino et al., 2020) and in other Mediterranean countries (Medeiros et al., 2022; Plieninger et al., 2016) due to similar socio-economic patterns.

#### 4.2. Land-use legacy influences on post-abandonment forests

Post-abandonment forests cover 29 % of the study watershed area (i. e., Fiolera catchment) as a result of secondary successions. During ecological successions, the diversity of flora and fauna changes (Denslow, 1980; Southwood et al., 1979). In the early stages of woody encroachment, patch edges are temporarily invaded by heliophilous woody species and shade-tolerant herbaceous species, increasing

biodiversity and litter cover (Wieczorkowski & Lehmann, 2022). Biodiversity decreases in the final stages, when ecotone areas are reduced (Niedrist et al., 2009). The contraction of open semi-natural ecosystems leads to a decrease in key species whose natural habitats have often disappeared (Fontana et al., 2014; Laiolo et al., 2004; Wieczorkowski & Lehmann, 2022).

In the surveyed post-abandonment forests, we observed differences in forest overstories and understories derived from different land-use legacies, mainly based on the historical presence or absence of a woody component. Indeed, in forest overstories derived from abandoned grasslands, the woody encroachment was mainly driven by pioneer species (63 % of the total basal area), such as *Betula pendula*, *Acer pseudoplatanus* and *Fraxinus excelsior*. This is consistent with the species composition reported for secondary colonisation of former grasslands in the Mediterranean mountain ranges (Alberti et al., 2009). *Fraxinus excelsior*, for example, was typically favoured as a solitary tree near shepherds' shelters because its leaves provided fodder for livestock when grass was not available, e.g., during late snowfalls (Bargioni & Zanzi Sulli, 1998). These trees are important biological legacies that act as a seed source and habitat for the recolonisation of a site, affecting ecosystem recovery patterns (Manning et al., 2006). *Fagus sylvatica* dominated forests originating from former grasslands, although it is typically established after initial colonisation by pioneer species. The presence of *Fagus sylvatica* in some grassland patches might be due to several concurrent ecological causes, such as the gap-filling dynamic in open areas enclosed by *Fagus sylvatica* stands. Indeed, the variability of successional stages may depend on several factors (Pedersen et al., 2023), such as the presence of seed-bearing individuals (Manning et al., 2006), improved soil fertility due to previous grazing activities (Koerner et al., 1999), or the phytotoxic effect of *Fraxinus excelsior* trees (Marigo et al., 2000). Indeed, understory species indicated good soil nutrient levels, which may be related to previous fertilisations typical of managed grasslands or simply to the fact that fertile soils were traditionally dedicated to pastures and meadows (Mollier et al., 2022). The presence of open light conditions also suggested less advanced successional dynamics. In addition, a higher PV and the presence of ruderal and grassland species indicated that historical management continues to influence these forests, increasing their suitability for grazing. The presence of a mixed overstory dominated by pioneer species, along with an understory of heliophilous, ruderal, and grasslands species, suggests that these forests, established in abandoned grasslands, are in the early stages of succession. Typically, forests originating from former grasslands were found in favourable areas on gentle, sunny slopes and in close proximity to human infrastructures. Due to their accessibility, management practices ceased later, so the reforestation process occurred more recently (Falcucci et al., 2007).

Post-abandonment forests derived from wooded land-use legacies (i. e., former wood-pastures and sparse forests) exhibited successional dynamics at advanced stages. Indeed, they were dominated by an older, late successional overstory and a shade-tolerant understory typical of woodlands and megaforbs. These post-abandonment forests were observed in the upper and more remote parts of the watershed, historically covered by *Fagus sylvatica* stands exploited for fuelwood and charcoal (Motta & Garbarino, 2003). *Fagus sylvatica* is a facultative seeder that forms pure and close forests with a limited herbaceous layer (Madsen et al., 2010). The dense cover and recalcitrant litter of *Fagus sylvatica* limit seed germination of other species, whereas *Fagus sylvatica* is advantaged by agamic renewal. These post-abandonment forests were located in marginal areas, often abandoned first because of their limited accessibility and difficulty of exploitation for arable agriculture or other intensive agricultural activities (Falcucci et al., 2007; MacDonald et al., 2000).

Although a successional dynamic emerged, we did not observe any statistical differences between the forests established in former wood-pastures and sparse forests. The land-use legacies identified through the photointerpretation of the LULC on the historical image did not

appear to be a sufficient condition to fully discriminate the high variability of overstory and understory observed in the studied post-abandonment forests. However, we detected different successional stages depending on land-use legacies and mainly referable to the historical presence or absence of a woody component. These differences in successional dynamics can be an important information for prioritising and zoning the management of post-abandonment forests.

Colonisation processes are the result of the interaction of many variables, some of which were not considered in this analysis, such as microclimatic conditions, soil characteristics, and the interaction between taxa (Pedersen et al., 2023). Furthermore, some limitations related to the reduced sample size and the approximation error incurred in correlating land-cover with human land-use may have biased the analysis. For instance, grazing can delay successional dynamics, depending on grazing animal species, management technique, and stocking rates (Pittarello et al., 2020). Indeed, livestock trampling can promote open and eroded areas favourable to germination of pioneer species or even increase vegetation growth by improving soil fertility (Gillet et al., 2016; Muller et al., 1998; Olff & Ritchie, 1998). In addition to grazing, mowing of hay meadows can influence successional dynamics (Bakker et al., 2002). Periodic removal of aerial biomass affects seed dispersal, and thus competition and germination conditions, with consequences on the species diversity depending on the number of mowing per year (Bakker et al., 2002).

#### 4.3. Management implications for post-abandonment forests

Management of complex ecological systems such as mountain landscapes characterised by strong waves of land abandonment requires multidisciplinary and multiscale approaches (Garbarino & Weisberg, 2020). Their management can have different aims, which fall into two main strategies: (I) passive restoration through natural reforestation to allow old-growth conditions and (II) maintenance or restoration of traditional semi-natural landscapes (Navarro & Pereira, 2012; Perino et al., 2019). Natural reforestation is a passive and cost-effective approach that offsets the ongoing deforestation process on a global scale and improves the regulation of the water cycle (García-Ruiz et al., 2008) and the reduction of soil erosion (García-Ruiz & Lana-Renault, 2011), but results in a loss of landscape heterogeneity (Lasanta et al., 2015). On the contrary, active restoration of traditional semi-natural landscapes fosters a heterogeneous mosaic pattern of the landscape, but at the high costs required for its planning and implementation. Thus, the management decision process must consider the social (e.g., socio-economic and cultural interests) and political (e.g., European policies – Common Agricultural Policy and Natura 2000 network– and national and territorial – protected areas – policies) needs of the specific territory through its meticulous zoning and prioritisation (Benjamin et al., 2008; Lasanta et al., 2015; Navarro & Pereira, 2012). Active restoration of traditional landscape patterns is a viable alternative if long-term planning integrates ecological and conservation value and the socio-economic needs of the land. It is suitable when the goal is to restore or maintain habitats with early successional stages and/or associated with human activities (Navarro & Pereira, 2012). On the other hand, passive management emphasises more dynamic and stable ecological processes in the long term. Both must involve monitoring of natural dynamics to avoid collapse of ecosystem and associated services (Navarro & Pereira, 2012). The decision between passive and active restoration is often complex (Bell et al., 2020). A suggested solution is often to employ both strategies within the same region, involving localised and tailored restoration techniques that better support biodiversity and ecosystem goals rather than widespread rewilding initiatives (Benayas et al., 2008; Plieninger et al., 2014; Robledano-Aymerich et al., 2014).

The observed differences in successional stages among the studied post-abandonment forests depending on land-use legacy can provide an interesting perspective to help prioritise and zoning management

approaches. Implementing active management in post-abandonment forests established in abandoned grasslands can be strategic due to the presence of ecological conditions similar to the pre-abandonment ones and far from the natural trajectories (i.e., a less diversified forest structure, a pioneer overstory, and an abundant presence in the understorey layer of species typical of grasslands), improved accessibility to the sites, and higher suitability of the understorey to grazing and mowing, allowing for lower intervention costs (e.g., easier mechanisation favoured by the proximity to existing roads and buildings, higher PV) (Fig. 6). In contrast, post-abandonment forests established in areas with pre-existing wood formations (i.e., former sparse forests and wood-pastures) could be managed with passive restoration activities due to their advanced successional stage (i.e., an overstorey structure more diversified and dominated by species close to the natural potential vegetation, and an understorey dominated by typical woodland species), the limited accessibility and suitability for grazing and mowing, and thus higher intervention costs for the same outcome. This approach employs both passive and active management, avoiding altering successional dynamics close to natural trajectories and optimising the management of post-abandonment forest through targeted interventions in areas related to ecological conditions more suitable for grasslands restoration (Pelorosso et al., 2011). We believe that this methodology could contribute to the discussion of managing post-abandonment forests. It provides a valuable analytical framework for prioritising interventions and selecting more feasible and efficient management strategies for planning these landscapes (Marignani et al., 2008; Navarro & Pereira, 2012; Pelorosso et al., 2011)(Fig. 7).

### 5. Conclusions

Following land abandonment, post-abandonment forests represent an important component of current landscapes across the Alps (Anselmetto et al., 2024). Effective management of these landscapes requires a comprehensive understanding of their features, including the effects of former land-uses, as their legacies shape current and future ecological dynamics (Bürgi et al., 2017; Garbarino & Weisberg, 2020; Meli et al., 2017). Our study has quantitatively demonstrated that successional stages in post-abandonment forests vary depending on land-use legacies (e.g., the historical presence or absence of pre-existing tree stands, fertilisation processes, pastoral activities). These findings offer a valuable insight for selecting appropriate management strategies for post-abandonment forests, identifying where passive or active restoration would be more suitable. For instance, post-abandonment forests established on former grasslands may be suitable for active restoration due to their earlier successional dynamics. These forests are often more accessible to existing infrastructure and suitable for grazing and mowing, making active restoration a feasible and cost-effective approach. Conversely, pre-existing wood formations, such as former sparse forests or wood-pastures, tend to exhibit more advanced successional stages and may benefit more from passive restoration because of their limited accessibility and closer proximity to natural trajectories. This framework is particularly useful in regions where spatially explicit historical records are limited, making it challenging to trace the LULC history. In this way, land managers can leverage land-use legacies to optimise the management of these complex post-abandonment forest landscapes, even decades after abandonment, resulting in more efficient

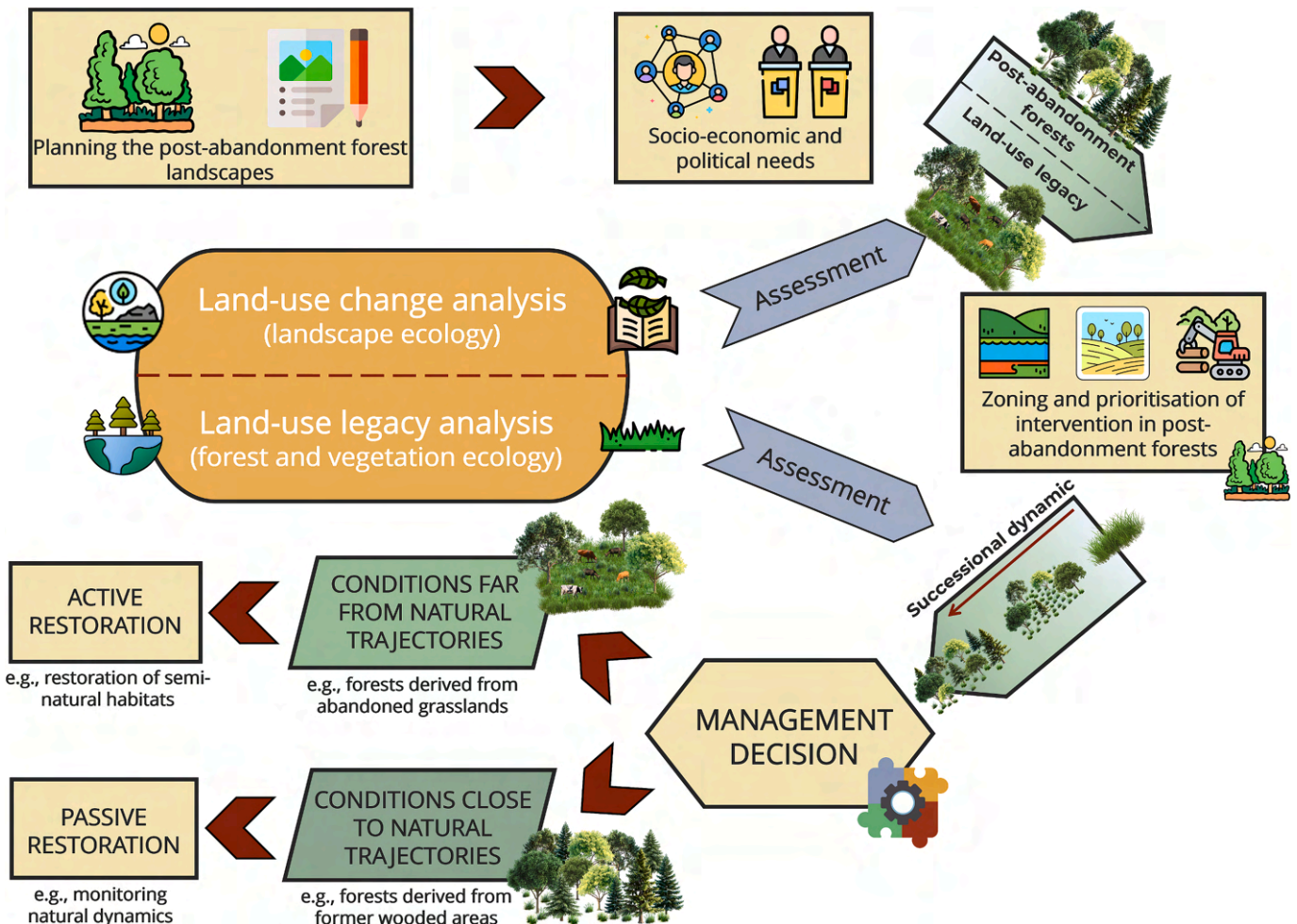


Fig. 7. Conceptual representation of management strategy prioritisation process of post-abandonment forests based on land-use change and legacies analysis.

and targeted interventions.

### CRedit authorship contribution statement

**Giacomo Marengo:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nicolò Anselmetto:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Davide Barberis:** Writing – review & editing, Investigation, Formal analysis. **Giampiero Lombardi:** Writing – review & editing, Methodology. **Michele Lonati:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Matteo Garbarino:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.landurbplan.2025.105357>.

### Data availability

Data will be made available on request.

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