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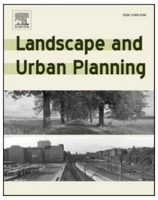

Review Article

# Global change in the European Alps: A century of post-abandonment natural reforestation at the landscape scale

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## HIGHLIGHTS

- European Alps have a long history of LULCC research spanning 150 years.
- The spatial distribution of LULCC studies is heterogeneous across the Alps.
- Reforestation was greatest in remote and sparsely populated municipalities.
- Reforestation was higher in south-facing slopes of dry marginal landscapes.
- A dynamic harmonised LULCC database is needed to analyse post-abandonment trends.

## ARTICLE INFO

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## ABSTRACT

Natural reforestation is one of the dominant processes in marginal mountain areas of the Northern hemisphere. There is a globally relevant need to predict where and when natural reforestation is likely to occur and what the ecological and social effects might be. We conducted a systematic review and *meta*-analysis of land use/land cover change (LULCC) case studies investigating spatial patterns of post-abandonment natural reforestation in the European Alps. We selected the Alps as representative of global change effects on forests due to their history of LULCC since the 19th century. Our aim was to identify the most important socio-ecological influences on reforestation and discuss implications for planners and managers. At the regional scale, we summarised the spatiotemporal distribution and methodological approaches of the case studies. At the municipality scale, we explored the relationships between reforestation rate and socio-economic variables using multivariate statistics. At the landscape scale, we assessed climate, topographic, and socio-economic drivers on reforestation using Random Forest regression. We observed a lack of studies in the northeastern region of the Alps. Population density, road density, and the proportion of workers employed in industrial vs. agricultural job sectors were the variables most highly correlated with reforestation. Reforestation rate was greatest in south-facing slopes of dry landscapes within remote and sparsely populated municipalities. We advocate for a dynamic harmonised LULCC geodatabase to capture the nonlinearity of past LULCC in training both correlative and process-based models for landscape planning.

## 1. Introduction

Human action has been a dominant force shaping Earth systems for millennia, affecting the ecological structure of landscapes and the provision of ecosystem services (Ellis et al., 2013; Lewis & Maslin, 2015). During the Anthropocene, land use/land cover change (LULCC) and climate change has affected forest ecosystems by dampening species diversity and distribution, increasing tree mortality, and altering disturbance regimes (e.g., Seidl et al., 2017; Mantero et al., 2020; McDowell et al., 2020). To date, LULCC is considered to be the most important global change component in affecting terrestrial ecosystems, despite predictions that in the future climate change will equal or surpass the role of LULCC (Oliver & Morecroft, 2014; Newbold, 2018). While tropical deforestation in areas where forests are increasingly being converted to agricultural lands is of great global concern (FAO, 2020; Fagan et al., 2022), the post-abandonment natural reforestation of

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former agricultural lands also represents a major land use change of global importance (Meli et al., 2017; Ward, 2019). Despite local post-abandonment reforestation may occur in areas where the dominant LULCC processes at the regional scale are deforestation, urbanisation, and agricultural land expansion (e.g., Latin America, Africa, and tropical Asia; Crawford et al., 2022; Díaz et al., 2011), land abandonment is usually associated with high-income countries in the Northern hemisphere (e.g., Ramankutty et al. (2010) and Martinuzzi et al. (2015) for the US; MacDonald et al. (2000) and Plieninger et al. (2016) for Europe; Uchida et al. (2018) for Japan).

The European Alps (hereafter, Alps) are paradigmatic in this sense; human settlements in the Alps became particularly important at the end of the Würm glaciation (i.e., 12 000 before present), with an increase of population starting from the Neolithic and Bronze Age (i.e., 8000 to 3000 BP) (Carcaillet, 1998; Favilli et al., 2010). During that period, evidence shows how slash-and-burn practices were largely adopted across the Alps to create open areas for pastures and agriculture (e.g., Carcaillet, 1998; Tinner et al., 2005; Carcaillet et al., 2009). Since then, Alpine landscapes have been modified by the exploitation of forests for timber and fuelwood, grazing, mining practices, and maintenance of agricultural land (Mietkiewicz et al., 2017). In the last millennium, societal changes and consequent land use are associated with historical shifts in climate (e.g., Medieval Optimum and Little Ice Age; Büntgen et al., 2016). The industrial revolution of the 19th century led to an intense exodus from the marginal valleys of the Alps towards urban and industrial centres, resulting in widespread natural reforestation following agricultural abandonment (MacDonald et al., 2000; Mietkiewicz et al., 2017; Gelabert et al., 2022) and shaping new post-modern landscapes (Antrop, 2005). Nevertheless, patterns of abandonment may vary locally, with an intensification of agriculture in districts with more favourable environments, greater productivity, and closer connections to transportation corridors and population centres, but an enduring abandonment of environmentally harsh and remote areas (MacDonald et al., 2000; Egarter Vigl et al., 2016). Therefore, even as the area used for agriculture has declined over time, the intensity of use has increased in the remaining agricultural areas. For example, the number of livestock in the Alpine countries has declined by 16 % over the last 60 years, but the livestock density (LAU $ha^{-1}$) has increased by 6 % over the same period (–22 % and + 10 % respectively for Europe as a whole) (FAOSTAT, 2022).

Following agricultural abandonment in the Alps, secondary succession has led to a natural reforestation of areas that had been converted to croplands and pastures for millennia. At lower elevations, secondary succession consisted of in-filling of non-forest patches such as abandoned meadows, grasslands, and arable lands (Garbarino et al., 2020). At the treeline ecotone, LULCC is considered the most important factor determining treeline position and change in areas with a prolonged history of agriculture or resource exploitation (Gehrig-Fasel et al., 2007; Garbarino et al., 2020; Anselmetto et al., 2021). Social and cultural transformations are the leading drivers of land use change at the global scale (Crawford et al., 2022), but topography, microclimate, road availability, and population become fundamental drivers of reforestation at the landscape scale (Garbarino et al., 2020; Gelabert et al., 2022). The synergic effect of social and ecological conditions can be difficult to disentangle, as is true for the interplay between land use legacies and climate change (Gehrig-Fasel et al., 2007; Ameztegui et al., 2016; Anselmetto et al., 2021).

Post-abandonment natural reforestation can provide a restoration opportunity to establish trajectories towards ecologically functional landscapes (Navarro & Pereira, 2012; Plieninger et al., 2016), but this must be weighed against the threats for reduced biodiversity, increased risk of natural disturbances associated with closed-canopy forests, and potentially diminished cultural values. From a conservation point of view, large carnivores and old-growth specialist birds have been favoured by the widespread natural reforestation of mountain ecosystems of the Alps (Chapron et al., 2014; Bani et al., 2019; Davoli et al., 2022). However, many plant and animal species associated with historical anthropic disturbances benefit from the presence of forest edges and semi-natural landscapes (Bani et al., 2019; Betts et al., 2019). Moreover, many landscapes experiencing post-abandonment reforestation are particularly sensitive to natural disturbances, given the permeability of continuous forest cover associated with land abandonment (Mantero et al., 2020). For instance, many large wildfires struck the Western Italian Alps in 2017, affecting around 10 000 ha (Morresi et al., 2022). Finally, post-abandonment reforestation dampens aesthetic and cultural functionalities of the so-called anthromes (anthropic biomes) (Halada et al., 2011; Egarter Vigl et al., 2016; Schirpke et al., 2021). Most of these abandoned landscapes, such as the larch wood pastures and terraced landscapes of the Alps – but also *Satoyama* in Japan and *dehesa* systems in the Iberic peninsula – are considered cultural landscapes, and concern over their conservation is increasing all over the world (Fischer et al., 2012; Perino et al., 2019).

The complexity of natural reforestation processes and their socio-ecological outcomes demands proper analytical scales to quantify and model spatial and temporal patterns of change (Garbarino & Weisberg, 2020). Ecosystem functioning and recovery and the socio-economic conditions of land abandonment are key factors when choosing tools and scales of analysis. For instance, land abandonment is only a temporary condition in some regions of the world (Crawford et al., 2022), but it can be permanent or long lasting in many others, such as the Alps (MacDonald et al., 2000; Plieninger et al., 2016). In these long-lasting abandoned ecosystems, natural vegetation recovery and reforestation have been ongoing over past decades to centuries, and land use legacies are still driving trajectories of change (McDowell et al., 2020). Given strong local influences of land use legacies and the fine-scale patchiness of secondary successional processes (i.e., in-filling of small, grass-dominated patches by woody species), fine spatial and at least decadal temporal resolutions are needed to capture their heterogeneity (Orlandi et al., 2016; Meli et al., 2017). The Alps have been the subject of numerous landscape ecological investigations of LULCC. However, many case studies from this region report inferences developed from inconsistent remote sensing data sources and analytical approaches, lacking a common and harmonised approach.

Based on this gap of knowledge and with the intention of providing a consistent framework for analysis, the overall aim of our study was to conduct a systematic literature review and *meta*-analysis of natural reforestation across the Alps over a range of scales from landscapes to large municipalities. Specifically, our objectives were (a) to collect methodological and spatiotemporal information on natural reforestation research across the region, (b) to analyse the relationship between socio-economic variables and forest gain at the municipality scale, (c) to explore and quantify influences of climate, topography, and anthropogenic drivers on natural reforestation processes at the landscape scale, (d) to discuss future directions in managing post-abandonment natural reforestation from a landscape planning perspective.

## 2. Materials and methods

### 2.1. Study area

The Alps extend over 1200 km from southeastern France to northwestern Austria (Alpine Convention, 2018), showing significant topographic variability comprising extensive lowlands, steep valleys, and mountain peaks rising above 4800 m a.s.l. The Alps host more than one-third of European flora, with several endemic taxa (Fauquette et al., 2018). Oak forests (*Quercus* spp.) dominate at lower elevations, silver fir (*Abies alba* Mill.) and beech (*Fagus sylvatica* L.) are associated with mesic regions, and Scots pine (*Pinus sylvestris* L.) with xeric slopes of the montane belt. European larch (*Larix decidua* Mill.), Norway spruce (*Picea abies* (L.) H. Karst.), and Stone pine (*Pinus cembra* L.) dominate the subalpine belt. Mean annual temperatures range from less than 0° to 10° C. Annual precipitation in the region ranges from 400 to 3000 mm, with topographic effects acting at different spatial scales (Isotta et al., 2014). Climate change is already affecting the region and is expected to increase summer and winter temperatures and alter precipitation regimes (Pörtner et al., 2022). Because of their long land use history and excellent availability of long-term data, the Alps are a perfect study system for investigating the phenomenon of post-abandonment natural reforestation.

### 2.2. Systematic review

The workflow of this study consisted of two main phases (Fig. 1): (i) a systematic review of the scientific literature to retrieve data on LULCC dynamics of diverse case study landscapes within the Alps (location, scale of analysis, methodology), and (ii) a *meta*-analysis of the selected case studies to quantify the influences of several key socio-ecological drivers on forest gain. To conduct our literature review, we searched the main scientific literature databases (Scopus, ISI Web of Science, and PubMed) on 10 February 2022. The search query as applied in Scopus was TITLE-ABS-KEY ((“land use” OR “land-use” OR “land cover” OR “land-cover” OR “land abandonment” OR “landscape change”) AND forest* AND (alps OR “alp* region”)). After combining the publications obtained from Scopus, WoS, and PubMed, our systematic review identified 458 unique articles. The first screening of titles and abstracts was used to remove duplicates and select only those landscapes located within the Alps. The remaining articles were then thoroughly read to ensure that inclusion criteria were met. We chose only case study landscapes that (i) analysed LULCC changes through a polygon-based change detection, (ii) included forested areas, and (iii) had a spatial

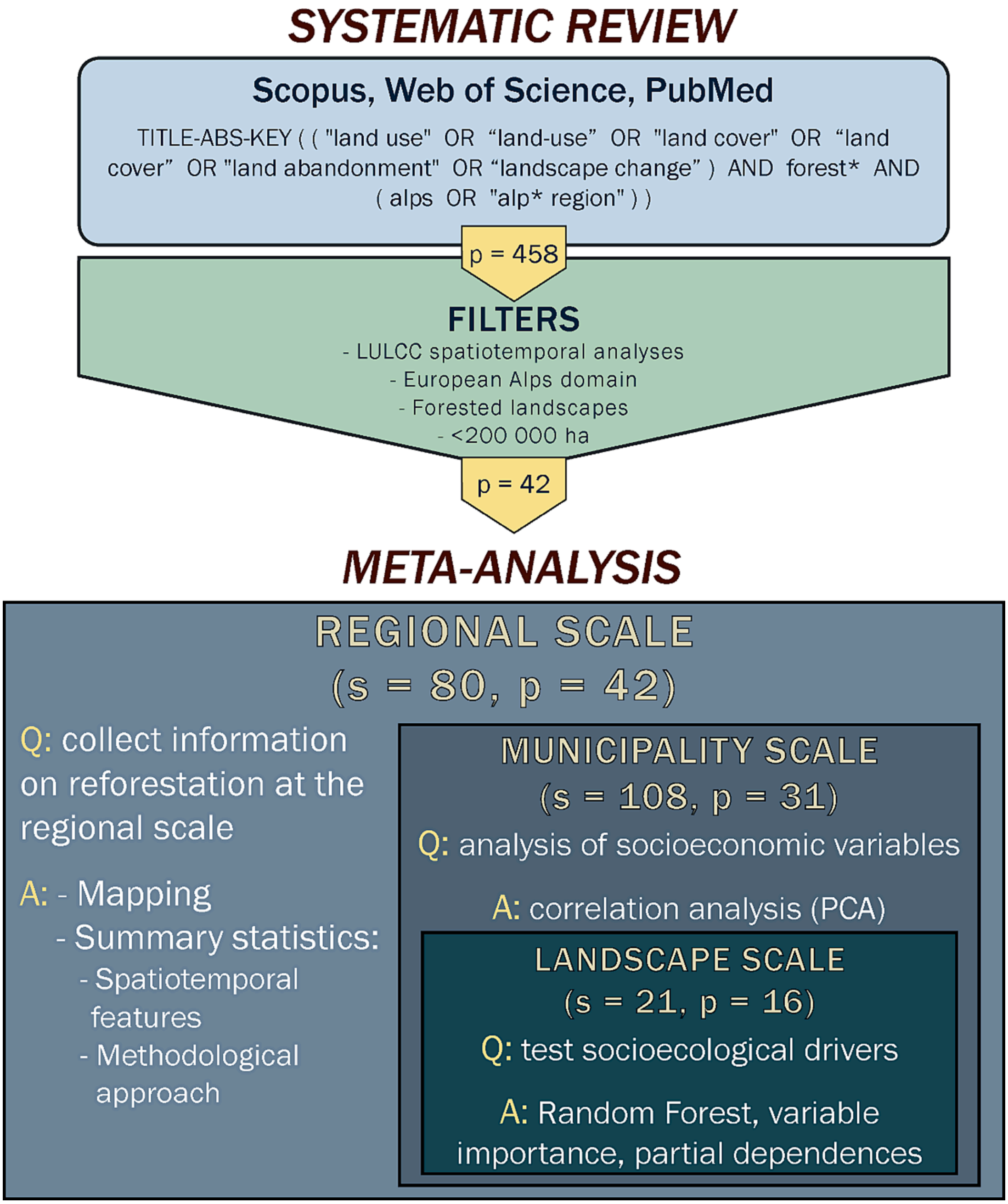

**Fig. 1.** Conceptual workflow of the study from the systematic literature review to the *meta*-analysis. Q = scientific questions/objectives associated with each scale of analysis; A = analytical tools associated with each scale of analysis; p = number of papers in each methodological step; s = number of sites analysed in the present study for each scale (i.e., case studies at the regional scale, municipalities at the municipality scale, and landscapes at the landscape scale).

extent smaller than 200 000 ha. As a result, we obtained a total of 42 relevant articles for the *meta*-analysis (Appendix Table A1).

### 2.3. Scales of analysis

From the selected articles, we derived a set of unique case studies. A single research article may have analysed multiple sites; also, the same site may have been investigated in several articles. In the latter case, we selected the study with the longest temporal extent. We analysed several aspects of reforestation across three spatial scales (Fig. 1). At the regional scale (reg) we included spatially defined case studies located within the Alpine Convention Perimeter (sites = 80) for which the forest gain was not reported in the articles. We used this scale to summarise methodological approaches and spatiotemporal characteristics of the studies across the entire region. As a reference, we used the Nomenclature of Territorial Units for Statistics (NUTS, 2021).

The municipality scale (mun) consisted of spatially defined studies reporting forest change. We selected observed annual forest gain per site (% of increase year$^{-1}$) as our measure of reforestation since it was the only forest gain variable common to all the studies. We derived this information either directly from the articles' main text and supplementary materials or by calculating it from absolute or relative values whenever feasible. We assumed that, in the Alpine region, the forest gain over the last 100 years has been mostly related to post-abandonment natural reforestation (hereafter, reforestation) and climate change, with novel afforestation due to plantation forestry playing only a minor role (Gehrig-Fasel et al., 2007; Tasser et al., 2007, 2017; Garbarino et al., 2020). We chose relative over absolute increase because larger landscapes tended to be in close proximity. Had we used the absolute increase as our measure, our findings would have been biased towards large-area studies and therefore would have over-emphasized only a subset of the overall Alpine region. At this scale, we selected only landscapes that could be attributed to a municipality (108 municipalities) according to Local Administrative Units (LAU) level 1 (LAU, 2021).

The landscape scale (lan) included landscape studies from which it was possible to derive precise spatial attributes such as geographic position and surface area (s = 21). Nevertheless, since few authors showed the land cover maps they used in their research, we made the simplifying assumption that study landscapes were circular in shape. We determined a circular buffer around the centroid of each landscape, with radius length calculated such that buffered areas would match the study area extents reported in the literature and the centroid represented the coordinates provided by the authors.

### 2.4. Socio-ecological predictors

We selected a set of socio-economic, topographic, climate, and vegetation variables that we tested with respect to forest gain rate at the municipality and landscape scales (Table 1, Appendix B). Ecological and socio-economic constraints can be considered the two main drivers of post-abandonment reforestation (Garbarino et al., 2020; Gelabert et al., 2022). We compared the observed forest gain as synthesized from the articles in our *meta*-analysis to the recent forest cover change rate derived from satellite remote sensing using the Corine Land Cover (CLC; European Commission, 1994) for the period 2000–2018. The CLC has been widely applied for mapping habitats, assessing biodiversity, analysing landscape fragmentation and developing future land use scenarios (e.g., Lehsten et al., 2015). Nevertheless, the CLC has performed poorly in estimating agricultural abandonment and quantification of forest expansion, especially related to small patches (i.e., < 5 ha) processes (Kuemmerle et al., 2016; Pazúr & Bolliger, 2017; Lieskovský & Lieskovská, 2021). Our aim was to assess our long-term fine scale dataset derived from discrete study site locations against this widely used medium resolution wall-to-wall dataset. We excluded 1990 CLC to include Switzerland, for which data are unavailable for the first year of analysis (Appendix B). At the landscape scale we explored more general patterns by adopting a series of ecological drivers at 1-km spatial resolution and socio-economic variables. We selected this coarse spatial resolution due to the exploratory objective of our study and the uncertainty in attributing spatial position to the landscapes.

We analysed municipality and landscape scales separately because there were few articles in our database that provided sufficient spatial

**Table 1**
Socio-ecological predictors used in the study, divided by category. Job sectors are classified as primary (i.e., agricultural/natural resource), secondary (i.e., manufacturing), and tertiary (i.e., service).

| Category | Variable | Data source | Spatial resolution | Scale of analysis |
|---|---|---|---|---|
| Socio-economic-Population- | Population density (1961, 1971, 1981, 1991, 2001, 2011, 2020) | Eurostat | Municipality | munlan |
| | Population change (1961–2020) | Eurostat | Municipality | munlan |
| | Population rate of change (1961–2020) | Eurostat | Municipality | munlan |
| Socio-economic-Agriculture- | Job sectors employment (primary, secondary, tertiary) | Alpine Convention atlas | Municipality | mun |
| | Relative change in number of farms (1990–2000) | Alpine Convention atlas | Municipality | mun |
| Socio-economic-Remoteness- | Tourism density | OSM | Municipality | mun |
| | Road density (primary, secondary, tertiary) | OSM | Municipality | mun |
| | Cost of movement (min, mean, max) | OSM + MERIT DEM | 1 km | lan |
| | Distance from cities (min, mean, max) | OSM | 1 km | lan |
| | Distance from towns (min, mean, max) | OSM | 1 km | lan |
| Topography | Elevation (mean, standard deviation) | MERIT DEM | 1 km | lan |
| | Slope (mean, standard deviation) | MERIT DEM | 1 km | lan |
| | Topographic position index (mean, standard deviation) | MERIT DEM | 1 km | lan |
| | Heat load index (mean, standard deviation) | MERIT DEM | 1 km | lan |
| Climate -Mean values- | Precipitation (annual, summer, winter)(median, standard deviation) | CHELSA timeseries | 1 km | lan |
| | Mean temperature (annual, summer, winter)(median, standard deviation) | CHELSA timeseries | 1 km | lan |
| | Minimum temperature (annual, summer, winter)(median, standard deviation) | CHELSA timeseries | 1 km | lan |
| | Maximum temperature (annual, summer, winter)(median, standard deviation) | CHELSA timeseries | 1 km | lan |
| Climate -Slope of change- | Slope of precipitation change (1979–2013) | CHELSA timeseries | 1 km | lan |
| | Slope of mean temperature change (1979–2013) | CHELSA timeseries | 1 km | lan |
| | Slope of minimum temperature change (1979–2013) | CHELSA timeseries | 1 km | lan |
| | Slope of maximum temperature change (1979–2013) | CHELSA timeseries | 1 km | lan |
| Vegetation | Forest cover change (2000–2018) | Corine Land Cover | Municipality | mun |

precision to allow for a fine-scale analysis of topographic and climate predictors (landscape scale). Nevertheless, we did not want to lose information about the case studies where values of forest gain were provided, but the spatial positioning was not precise (municipality scale). For this reason, we used the latter to analyse broad socio-economic drivers and the differences between forest gain values in the articles and forest gain reported by the CLC.

### 2.5. *Statistical analysis*

At the municipality scale (mun), we analysed the multivariate correlation between observed forest gain, socio-economic conditions, and satellite-derived forest gain through Principal Component Analysis (PCA). We transformed the data to meet normality assumptions either through logarithmic or square-root transformations.

At the landscape scale (lan), we created a Random Forest (RF) regression model using principal components of socio-ecological drivers as predictors and the annual forest gain (% year$^{-1}$) as the response variable. Due to the $p > n$ *problem* of machine learning, related to a low number of rows, we reduced the feature dimensionality through PCA prior to fitting RF models. We performed a PCA for each group of environmental drivers: socio-economic (Appendix Table B1), climate (Appendix Tables B2, B3), and topographic (Appendix Table B4), considering statistically significant principal components (PCs) that accounted for 75 % of the variability. We measured statistical significance using p-values derived from a Monte Carlo permutation test on 10 000 runs with randomized data. We adopted a nested fivefold repeated spatial cross-validation to tune the RF model and evaluate its performance (Lovelace et al., 2019). For tuning hyperparameters (number of variables tried at each split, number of trees, minimum node size, and sample fraction), we developed an optimization algorithm based on a random search within a search space using 50 steps. To evaluate the models and select the model of best fit, an outer 3-fold cross-validation resampling strategy was used. Mean absolute error (MAE), mean squared error (MSE), and root-mean-square error (RMSE) were estimated by averaging the values obtained from the resulting 300 models. We assessed variable importance of the RF model using the permutation method (Breiman, 2001). We ran a second RF regression using the main variables associated with the most influential PCs to derive partial dependence plots (Goldstein et al., 2015) on the marginal effect of each variable on the annual forest gain rate.

PCA was conducted in PC-Ord v7.08 (McCune & Mefford, 1999). All other analyses were conducted in R version 4.1.2 (R Core Team, 2021). See Appendix Table B5 for R packages used in the analyses.

## 3. Results

### 3.1. *Spatiotemporal characteristics of case studies*

We retrieved 42 papers that met our inclusion criteria. We observed an increasing trend of publication until 2020, with more than 50 % of publications occurring between 2007 and 2017. The topic is strongly multidisciplinary, with multiple research objectives including ecosystem services evaluation (e.g., Schirpke et al., 2013), natural disturbances risk analysis (e.g., Zgheib et al., 2020), land use change (e.g., Tasser et al., 2017), species distribution modelling (e.g., Carlson et al., 2014a), and assessment of reforestation drivers (e.g., Garbarino et al., 2020). We chose 80 eligible case studies according to our requirements (Fig. 2). The total extent covered by the 80 sites was 9257 km$^2$, corresponding to 5.17 % of the whole Alpine region surface area (~179 014 km$^2$) and the mean distance between each landscape was 210.71 km. The case studies belonged to 6 different countries (Austria, France, Germany, Italy, Slovenia, Switzerland), 25 different provinces (NUTS level 3), with Italy emerging as the most represented country (s = 48, 60

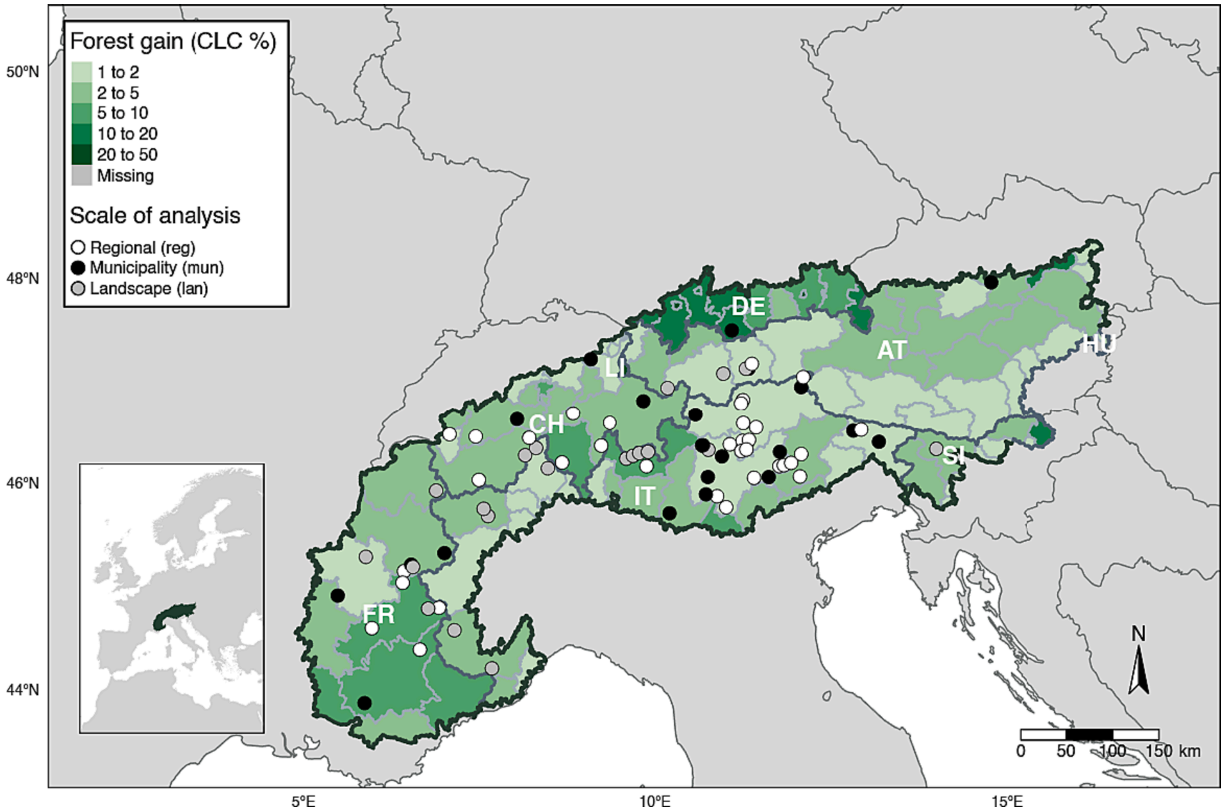

**Fig. 2.** Location of the case studies within the Alpine region (Alpine convention perimeter). Point symbol shading indicates the analytical scale. Green polygon shading show the forest gain at NUTS lv3 derived from Corine Land Cover for the period 2000–2018. The inset map shows the location of the European Alps within Europe. AT = Austria, CH = Switzerland, DE = Germany, FR = France, IT = Italy, LI = Liechtenstein, SI = Slovenia.

% of the total). We observed 17 provinces with more than one case study, with Trento (s = 16) and Bolzano-Bozen (s = 14) being the most studied. In addition to having the greatest number of study landscapes, Italy had the largest landscapes in terms of mean surface area. However, Austrian and French studies investigated LULCC with a longer temporal extent and a finer temporal resolution, often integrating historical maps (Fig. 3a). On average, we observed a comparable number of land cover classes within countries. Countries were similar in the numbers and types of case study characteristics used (Fig. 3a).

The largest site was Gemona (Italy; 114 800 ha), the smallest was Längenfeld (Austria; 100 ha) (Fig. 3b). Most of the studies derived forest gain data from both historical maps and aerial photos. Historical maps included the Siegfried map (Topographic Atlas of Switzerland), the Hasburgic map, and the Napoleonic cadastral map. Temporal extent (last year – first year) ranged from 12 years (Agordino, Italy) to 195 years (Waidhofen, Austria), with a mean value of 103 years and a standard deviation of 54 years (Fig. 3c). Regarding the temporal resolution, most studies (n = 25) adopted 2 or 4 different maps to analyse forest cover dynamics, with a maximum of 8 different time steps observed and an average value of 3.5 ± 1.5 (Fig. 3d). Most studies (n = 14) examined 5 land cover classes, with a minimum of 2, a maximum of 21, and a mean of 5.8 ± 3.0 (Fig. 3e).

### 3.2. Socio-economic drivers at the municipality scale

We analysed the relationship between observed forest gain and a set of socio-economic drivers at the municipality scale through principal component analysis. The first and second components accounted for 34.4 and 16.3 % of the total variation, respectively, while the third component accounted for the 14.8 % (Fig. 4, Appendix Fig. C1, and Table C1). The first PC axis was strongly associated with long-term (i.e., more than 60 years) dynamics such as the observed forest gain (negative association) and population (1961, 2020) and road density (positive association). The second component was mostly associated with recent dynamics such as job sectors (positive association with agricultural/natural resource and manufacturing sectors employees, negative association with the service sector employees), recent forest change through CLC, and recent farm change. Sites that experienced a higher forest gain were likely to have had lower population both in 1961 and 2020 and to have more workers in the agricultural/natural resource sector. Manufacturing sector employees (Pearson's r = – 0.29), agricultural/natural resource sector employees (r = 0.27), road density (r = – 0.28), and population density in 1961 (r = – 0.26) emerged as the most correlated variables to the observed forest gain. Forest gain derived from CLC analysis of the last 20 years (2000–2018) appeared to be uncorrelated (perpendicular) to the observed forest gain rate (r = – 0.03) (Fig. 4).

### 3.3. Socio-ecological drivers at the landscape scale

Prior to fitting the landscape-scale RF regression model, we reduced the number of variables through a principal component analysis, retrieving 8 principal components (Appendix B and Fig. C2). The climate PC associated with precipitation (Precipitation) was the most important in explaining forest gain, followed by human related variables (Remoteness and Population), and topography (especially the second PC, Topography_2). Climate change proved unimportant for predicting the forest gain rate (Fig. 5a). Due to the small number of observations at this scale (s = 21), errors calculated through the 300 iterations are quite noticeable (Appendix Fig. C3). From the second RF regression model, we

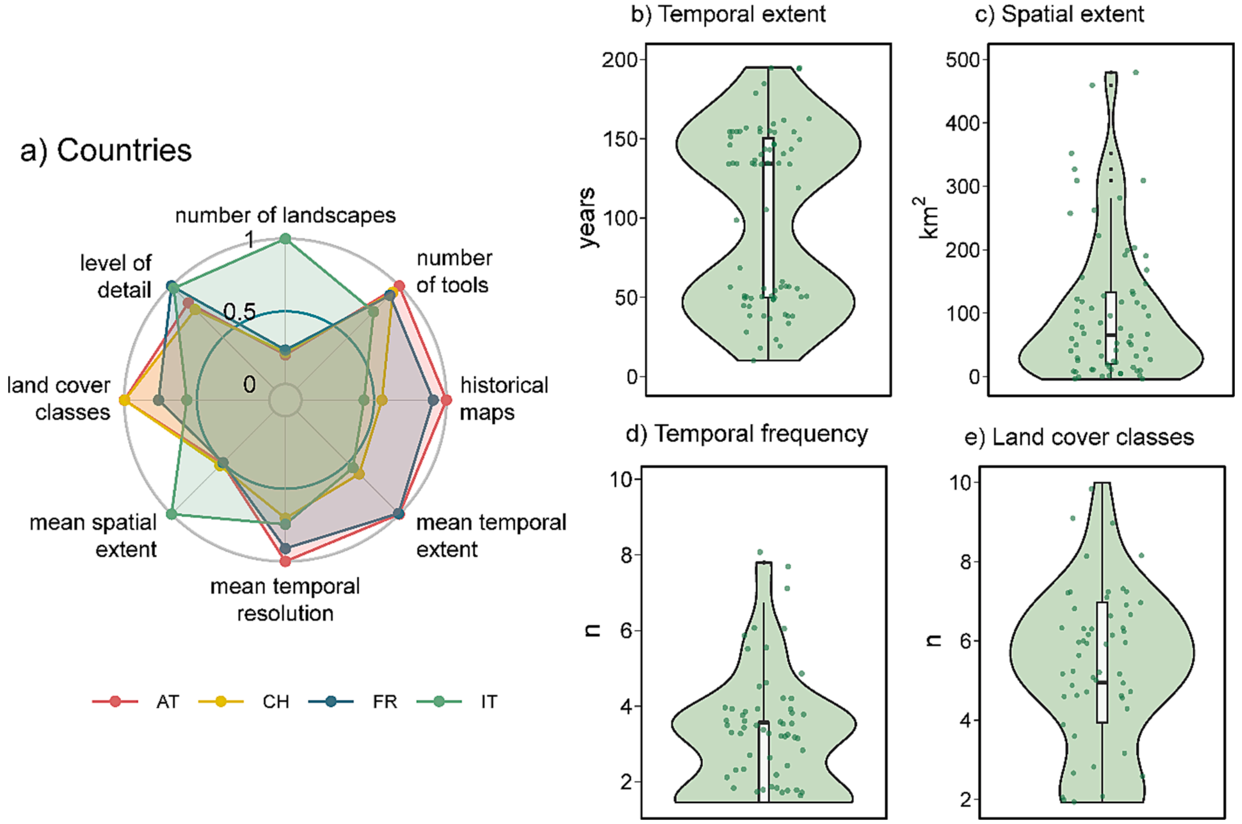

**Fig. 3.** Summary of case study characteristics (s = 80). (a) Radar plot on nine variables grouped by country (number of tools = number of different data sources and tools used to derive land cover information, historical maps = number of studies using historical maps, land cover classes = number of analysed land cover classes, level of detail = level of details about reforestation and spatial positioning provided for the study sites). Sources of land cover information. Violin plots and box plots display frequency distributions, median, and interquantile range for the (b) spatial extent of the landscapes; (c) temporal extent of the studies; (d) temporal frequency; (e) number of land cover classes.

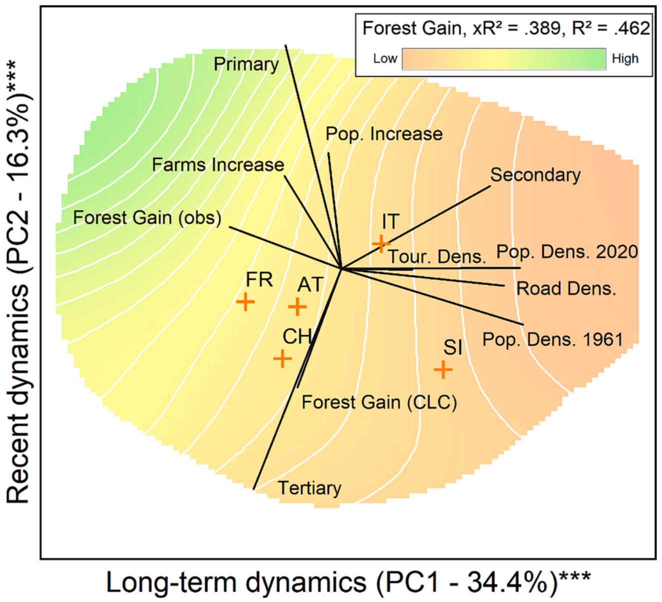

**Fig. 4.** Results of the principal component analysis at the municipality scale (s = 108). PC1 vs PC2. Principal components were significant ($p < 0.001$, Monte Carlo permutation test on 10 000 runs with randomized data). Country centroids are shown as orange crosses: AT = Austria, CH = Switzerland, FR = France, IT = Italy, SI = Slovenia. Forest gain gradient is represented as a 3D response surface and contour lines obtained through non-parametric regression against PC1 and PC2 scores. Flexibility was optimized according to the highest cross-validated fit ($xR^2$).

calculated partial-dependence plots for the main drivers of each of the four most important PCs. In particular, we assessed annual median precipitation (Precipitation; Fig. 5b), minimum distance from towns (Remoteness; Fig. 5c), population density of 1961 (Population; Fig. 5d), and mean heat load index (Topography_2; Fig. 5e). Forest gain rate was generally higher in landscapes with lower annual precipitation and population density, more than 50 km from towns, and on south-facing slopes.

## 4. Discussion

### 4.1. *Reforestation rate and pattern across the Alps*

Post-abandonment natural reforestation is a widespread phenomenon in many countries of the Northern hemisphere (Ellis et al., 2013; Haddaway et al., 2014; Crawford et al., 2022). The Alps provides an excellent study region for investigating this global phenomenon due to its long history of land use followed by more than one century of abandonment (MacDonald et al., 2000; Mietkiewicz et al., 2017). In our literature review, we observed a good availability of spatiotemporal forest cover data for the Alps. The case studies utilized covered a surface area of more than 5 % of the Alpine Convention area, and inclusion of grey literature studies would most likely have encompassed a greater area. High research interest in spatial analysis of reforestation has resulted in a multidisciplinary set of analytical perspectives and methods for us to synthesize in our review. We observed an unbalanced spatial density and location of case studies, probably due to the magnitude and perception of human action (Haddaway et al., 2014), with the Western Alps showing the highest density of studies. It is possible that the increased concern regarding post-abandonment reforestation and its ecological and economic effects have been greater in the Western rather than in the Eastern Alps because depopulation and rural exodus took place earlier in the Western sector (Batzing et al., 1996). For instance, Tasser et al. (2017) reported the twenty years between 1960 and 1980 as the most relevant period of land abandonment for the Stubai Valley (AT), consistent with the twenty years indicated by Krausmann et al. (2003) for the entire Austria (1950–1970). Furthermore, the Slovenian Julian Alps experienced land abandonment after 1945, only a half-century after the less favourable land was tilled at the beginning of the 20th century (Andrič et al., 2010). Conversely, in the Western Alps the industrial sector had already begun to supersede agriculture by the second half of the 19th century (Batzing et al., 1996; Farvacque et al., 2019).

Given the generally long-time frames since land abandonment has occurred within the region, it is not surprising that we observed an average temporal extent of around a century among the case studies. This time span may be particularly relevant for studies of post-abandonment reforestation, since the mean time required by passive restoration to recover biogeochemical functions has been measured globally as 35.5 ± 33.1 years, depending on factors such as ecosystem resilience, the type and intensity of land use legacy, and local edaphic conditions (Meli et al., 2017). Therefore, satellite remote sensing

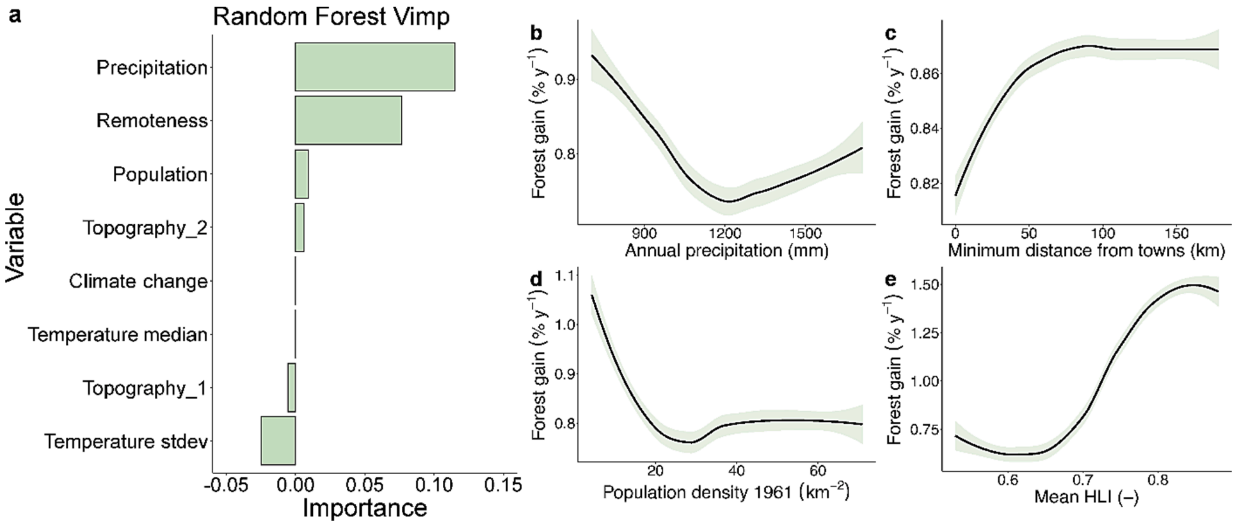

**Fig. 5.** Results of the RF regressions at the landscape scale (s = 21). (a) Variable importance of the RF regression on the principal components; partial dependence plots on (b) annual precipitation, (c) minimum distance from towns, (d) population density of 1961, (e) mean HLI.

timeseries (e.g., Landsat) and derived products (e.g., Corine Land Cover, CLC), spanning the last 30–40 years and lacking in fine spatial resolution, provide only a partial insight into this global process. Historical maps and aerial photos are fundamental tools to assess ecological responses to past land abandonment, given their longer temporal extent and finer (i.e., 1–10 m) spatial resolution (Garbarino et al., 2020). The first aerial photos emerged around World War II, and thus correspond well with the timing of abandonment in many landscapes. On historical aerial photos, cultural landscapes are often recognizable by the presence of patches of pasture enclosed in a forest matrix (Orlandi et al., 2016). The spatial mosaic of cultural landscapes is generally characterized by an interspersion of small patches with several ecological functions and structures. For this reason, they are often described as hotspots of ecosystem services worldwide (e.g., larch wood pastures in Austrian landscapes; Schirpke et al., 2013). Since post-abandonment reforestation usually consists of in-filling of these non-forested patches, a fine spatial resolution is crucial to monitor the loss of ecotones and the spatial simplification of a landscape.

Another important temporal feature to consider is the temporal resolution (i.e., the frequency of temporal observations for a given landscape). Even if satellite-based products have a higher temporal resolution (i.e., weeks/days), decadal land cover maps derived from aerial photos have the potential to inform managers and planners (Schneeberger et al., 2007; Carlson et al., 2014b) by capturing the nonlinearity of past LULCCs for more accurate prediction of future change scenarios (Carlson et al., 2014a). For instance, a series of aerial photos led to improved accuracy of future Business as Usual LULCC scenarios, by disentangling land use change- and climate change-dominated periods (Anselmetto et al., 2021). Also, correlations between temporal trade-offs of ecosystem services and the spatial arrangement of the landscape can be detected using multiple time steps of aerial photography (Egarter Vigl et al., 2016).

### *4.2. Drivers of reforestation across spatial scales*

Land abandonment is associated with regional socio-economic processes, but it also depends on conditions particular to a given landscape (i.e., climate, topography, infrastructures) that increase cultivation costs (Ameztegui et al., 2016; Crawford et al., 2022). On average, forest area increased at a net rate of + 0.64 % year$^{-1}$ across the case studies. This value was higher than the one described by Bebi et al. (2017) for the entire Alps (+0.37 % year$^{-1}$ from 1930) and the average annual rate of change reported by FAO (2020) for Europe (+0.29 % year$^{-1}$ from 1990 – 2020). At the municipality scale (mun), road and population density in 1961 had a strong negative correlation with forest gain. A sparse road network influences the cultivation cost, and marginal areas with weak infrastructure are the first to be abandoned (MacDonald et al., 2000; Ren et al., 2019). These abandonment patterns have been defined in the Forest Transition Theory (Mather, 1992; Díaz et al., 2011). Sometimes, good road infrastructure and increase in population lead to recultivation of abandoned areas (Crawford et al., 2022). We found a weak correlation between satellite-derived forest gain (2000–2018) and observed forest gain in the last century. This confirms our hypothesis that long-lasting human exploited areas that experienced a centennial land abandonment (i.e., Alps, Japanese *Satoyama* landscapes, or Spanish *dehesa*), characterised by a complex interspersion of patches, should be evaluated with a longer temporal extent and finer spatial resolution. Recent satellite-derived products suffer from a temporal mismatch between the diachronic analysis period and the duration of secondary successional processes.

The proportion of workers employed in the primary (i.e., agriculture and forestry) and secondary sector (i.e., industry) were respectively positively and negatively correlated to forest gain. This contradicts other findings that showed how national increase of workers in the off-forest sectors (i.e., secondary and tertiary) displaces land use outside borders, leading to an off-set of deforestation in other countries of the world and promoting reforestation (Pendrill et al., 2019). Employment data used in the study were taken for the year 2000, representing a momentary condition in a dynamic process. Moreover, mountain municipalities often occupy both the bottom part of a valley and its slopes, and the depopulation dynamics of a single farm, village, or slope could have affected reforestation rate more than depopulation when considered at the scale of the entire municipality. Nevertheless, analyses at the municipality scale are useful for landscape planning and decision systems in view of the increasing debate on wildness versus wilderness and passive restoration management (e.g., Meli et al., 2017; Ward, 2019; Schulte to Bühne et al., 2022).

Very few studies, from our literature review, provided spatially explicit data to perform exhaustive *meta*-analysis at the landscape scale (lan) because land cover maps were often an intermediate product of the analysis. Therefore, we used the annual forest gain rate as a proxy for landscape scale forest dynamics. Given the different time span of observations, the low number of landscapes, and the inability to accurately locate the case studies, our results offer a partial insight into global change effects on forest dynamics. Nevertheless, our results highlighted agriculturally unfavourable areas as hotspots of post-abandonment reforestation. In particular, sites characterized by a lower precipitation were more likely to experience intense forest gain, probably because landscapes with harsher ecological conditions and lower productivity are prone to be abandoned first, thus leading to a longer process of natural reforestation (MacDonald et al., 2000; Garbarino et al., 2020). It is interesting to note the increase of forest gain with an annual precipitation higher than 1200 mm. This high reforestation rate associated to a high primary production might occur in relatively high-elevation areas (hence, higher primary production) that had been agriculturally marginal by virtue of stony soils, colder temperatures, or shorter growing seasons. Human variables emerged as the second (i.e., remoteness) and third (i.e., population) most important driver, with higher forest gain in remote areas of low population that are also far from towns. Regarding topographical features, higher values of forest gain associated with high heat load values indicate a suitability for reforestation of southern slopes, where croplands and pasture had been concentrated in the past (Garbarino et al., 2020).

Climate change was one of the least important variables in the RF model. This supports the hypothesis that broad scale dynamics such as reforestation and forest gain are still mostly driven by land abandonment rather than climate change, even if a shift towards climatic-driven changes is expected (Martin et al., 2013; Ameztegui et al., 2016; Anselmetto et al., 2021). Global change affects abandoned mountain areas generating divergent processes of vegetation dynamics, with an in-filling of abandoned open areas at lower elevations, but with fragmentation of open areas and tree encroachment in the upper elevations (Gehrig-Fasel et al., 2007; Kulakowski et al., 2011; Anselmetto et al., 2021). In the lower mountain elevations, the rate of woodland expansion is gradually decelerating due to saturation of available space (Campagnaro et al., 2017). Above the treeline, active shrub and tree encroachment on semi-natural and natural alpine grasslands and unvegetated areas are likely due to warmer conditions during the growing season related to climate change (Bani et al., 2019; Choler et al., 2021).

### *4.3. Methodological insights: A plea for consistency*

Natural rewilding of landscapes with a long history of intensive human land use may create novel ecosystem conditions that require adequate monitoring, planning, and management to provide the services demanded by the society (Ward, 2019; Schulte to Bühne et al., 2022). Hence, there is a relevant need to quantify and predict where and when reforestation is likely to occur, and at what rate. Despite the availability of numerous case studies in the Alps, we observed the absence of a common protocol to analyse post-abandonment reforestation. Some papers encompassed more than one landscape (e.g., Zimmermann et al., 2010; Egarter Vigl et al., 2016; Tattoni et al., 2017; Garbarino et al., 2020) and integrated data from different previous studies, but without a regional scale approach. For this reason, we highlight the need for a harmonised geodatabase produced through a common land cover classification. We believe that a harmonised and dynamic land use change geodatabase encompassing an entire mountain region could serve as an accurate foundation for answering to several socio-ecological questions with global implication.

Landscape planning requires a profound knowledge of the land use history to assess forest ecosystem resilience and trajectories of change (Garbarino et al., 2020; McDowell et al., 2020). For instance, it would be useful for species distribution models to integrate dynamic scenarios of LULCC, characterized by fine spatial resolution and long temporal extent, with alternative climate scenarios (Martin et al., 2013; Carlson et al., 2014a). Policy decisions may benefit from a multi-scale assessment of reforestation (Schulte to Bühne et al., 2022). Regionally, an in-depth analysis of reforestation suitability can be used to quantify wall-to-wall reforestation probability or ecosystem services provision maps using logistic regressions with models trained on long-term data at the landscape scale (e.g., Díaz et al., 2011; Pellissier et al., 2013; Gelabert et al., 2022). This information may be integrated at the landscape scale, where reconstructing past dynamics of change may improve resources allocation and contrast land use legacies and climate change (Holl & Aide, 2011; Garbarino et al., 2020). A common LULCC dataset for the Alps can provide a monitoring tool for mountain ecosystem services such as cultural values, carbon sequestration, hydrologic regime, protection from natural disturbances, biodiversity, and conservation. Being able to reconstruct the history of LULCC and predict future scenarios of post-abandonment reforestation in mountain regions can drive the choice between passive restoration (i.e., rewilding) and active restoration of semi-natural ecosystems such as grasslands and agroforestry systems (Navarro & Pereira, 2012).

## 5. Conclusions

Abandoned rural landscapes in high incomes areas of the world such as the European Alps are expected to face a shift from land use change- to climate change-dominated stages (Martin et al., 2013). Indeed, assessing the long-term history of change and its land use legacy on forest dynamics should be the first step to plan future resilient landscapes (Beller et al., 2020; Garbarino & Weisberg, 2020). We observed several case studies across the Alps dealing with post-abandonment natural reforestation with the potential to fulfil this aim. The multidisciplinary nature of this topic is represented by studies which utilized disparate data sources and quantitative tools (e.g., historical maps, aerial photos, GIS environment) and research objectives (e.g., quantification of forest gain, driver of reforestation, future forecasting, analysis of multiple ecosystem services). Many studies have encompassed more than 100 years of change using a fine spatial resolution (i.e., 1–10 m) and with the potential to have a sufficient temporal resolution (i.e., 10–20 years). The importance of anthropic drivers for post-abandonment natural reforestation appeared both at the municipality and landscape scale. Population density, both in the past and currently, and the remoteness (i.e., road availability, distance to cities) of the municipalities and landscapes clearly emerged from our analyses, outdoing the role of climate change-related variables. In particular, reforestation rate was greatest in south-facing slopes of dry landscapes within remote and sparsely populated municipalities.

We advocate for a dynamic harmonised LULCC geodatabases integrating landscape case studies across the entire mountain region. Despite the high availability of data for the Alpine region, a comprehensive fine scale analysis across the entire region is still lacking. Therefore, there is a need to incorporate case studies from the grey literature and new landscapes where the density of available data seems scarce. We believe such a database can provide the foundation for predicting future trajectories of change both within the same region (e.g., Gelabert et al., 2022) and in other mountain regions where post-abandonment natural reforestation is a more recent process (i.e., China, India; Ren et al., 2019).

## CRediT authorship contribution statement

**Nicolò Anselmetto:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Peter J. Weisberg:** Methodology, Writing – review & editing. **Matteo Garbarino:** Conceptualization, Funding acquisition, Methodology, Writing – original draft, Writing – review & editing.

## 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.

## Data availability

A data table with the reviewed literature is provided in Appendix A (Table A1).

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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.2023.104973.

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