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Contrasting land use legacy effects on forest landscape dynamics in the Italian Alps and the Apennines

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# Landscape Ecology

## Contrasting land use legacy effects on forest landscape dynamics in the Italian Alps and the Apennines --Manuscript Draft--

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<b>Abstract:</b>	<p>Context</p> <p>Land use legacies of human activities and recent post-abandonment forest expansion have extensively modified numerous forest landscapes throughout the European mountain ranges. Drivers of forest expansion and the effects of changes on ecosystem services are currently debated.</p> <p>Objectives</p> <p>i) to compare landscape transition patterns of the Alps and the Apennines (Italy), ii) to quantify the dominant landscape transitions, and iii) to measure the influence of climatic, topographic and anthropogenic driving factors.</p> <p>Methods</p>	

	<p>Land cover changes and landscape pattern modifications were investigated at the regional (over 28 years, Alps and Apennines, Corine Land Cover dataset) and landscape scale (over 58 years, 8 Alpine and 8 Apennine sites, aerial images). The main driving factors of post-abandonment forest landscape dynamics were assessed with a statistical modeling approach.</p> <p>Results</p> <p>Forest expansion was the dominant landscape transition at both Italian mountain ranges, with an annual overall rate of 0.6%. Forest expansion was more extensive at lower elevations in the Apennines where climate is less limiting and extensive abandoned croplands and pastures were available throughout the study period. Distance from pre-existing forest edges in the Alps and elevation in the Apennines emerged as the most important predictors.</p> <p>Conclusions</p> <p>Forest expansion is most rapid where areas of recent agricultural abandonment coincide with favorable climatic conditions. The prediction of forest landscape dynamics, in these mountain forests with a long history of cultural use, requires knowledge of how the magnitude and timing of land use changes intersect spatially and temporally with suitable conditions for tree establishment and growth.</p>
<p><b>Response to Reviewers:</b></p>	<p>Dear editors and reviewers,</p> <p>we would like to thank you for your efforts revising our manuscript that we believe greatly benefited from your comments and suggestions.</p> <p>A table containing the reply to reviewers related to the manuscript entitled “Contrasting land use legacy effects on forest landscape dynamics in the Italian Alps and the Apennines” has been uploaded and appended to the main text of the manuscript. The table precisely answer to all reviewers' comments and refers to all the changes we made within the manuscript. The latter are highlighted in yellow within the Word document named “LAND-D-20-00035_R1.docx”.</p>

[Click here to view linked References](#)

## 1 **Contrasting land use legacy effects on forest landscape dynamics in the Italian Alps and the Apennines**

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17

## 18 **Abstract**

19 Context: Land use legacies of human activities and recent post-abandonment forest expansion have  
20 **extensively modified numerous** forest landscapes **throughout the** European mountain ranges. Drivers of  
21 forest expansion and the effects of changes on ecosystem services are currently debated.

22 Objectives: i) to compare landscape transition patterns of the Alps and the Apennines (Italy), ii) **to quantify**  
23 **the** dominant landscape transitions, and iii) to measure the influence of climatic, topographic and  
24 anthropogenic driving factors.

25 Methods: Land cover changes and landscape pattern modifications were investigated at the regional (**over**  
26 28 years, Alps and Apennines, Corine Land Cover dataset) and landscape scale (**over** 58 years, 8 Alpine and  
27 8 Apennine sites, aerial images). The main driving factors of post-abandonment forest landscape dynamics  
28 were assessed with a statistical modeling approach.

29 Results: Forest expansion was the dominant landscape transition at both Italian mountain ranges, with an  
30 **annual overall rate of 0.6%**. Forest expansion was more extensive at lower elevations in the Apennines  
31 where climate is **less** limiting and extensive abandoned croplands and pastures were available throughout  
32 the study period. **Distance from pre-existing forest edges in the Alps and elevation in the Apennines**  
33 **emerged as the most important predictors.**

34 Conclusions: Forest expansion is most rapid where areas of recent agricultural abandonment coincide with  
35 favorable climatic conditions. **Thus the prediction of forest landscape dynamics, in these mountain forests**  
36 **with a long history of cultural use,** requires knowledge of how the magnitude and timing of land use  
37 changes intersect spatially and temporally with suitable conditions for tree establishment and growth.

38 **Keywords** Forest expansion, cultural landscape, historical ecology, aerial photographs, landscape structure,  
39 land abandonment

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## 44 Introduction

45 Land use history exerts a strong long term legacy on forest landscapes, affecting their structure, spatial  
46 pattern and **associated** ecosystem services (Bellemare et al. 2002; Ziter et al. 2017). At a landscape scale,  
47 forests after their removal can be replaced by other land cover types such as crops, pastures, and  
48 settlements, which in turn can lead to habitat fragmentation. Land abandonment has important effects on  
49 natural disturbance regimes especially in regions with a long history of intensive human influence (Mantero  
50 et al. submitted). After land abandonment, secondary succession can lead to forest expansion, a complex  
51 dynamic process influenced by different factors such as climate, topography, seed availability and  
52 anthropogenic variables. An important driver at local scales has proven to be the former land use intensity  
53 and type (Walker et al. 2010). For example, abandoned **cropland**, with compacted soil due to former  
54 plowing, may experience slower successional dynamics than former pastures (Dupouey et al. 2002). A pan-  
55 European scale study over the last 25 years revealed that the most important landscape transitions are  
56 urbanization and natural afforestation processes, both affecting landscape service provision (Van der Sluis  
57 et al. 2019). In forest landscapes post-abandonment processes generally cause increased wildfire  
58 frequency, extent and severity (e.g. Moreira 2001; Lloret 2002; Pausas et al. 2012) and a decrease in the  
59 frequency and intensity of rockfall (Lopez-Saez et al. 2016; Farvaque et al. 2019) and avalanches  
60 (Kulakowski et al. 2011; García-Hernández et al. 2017). Post-abandonment forest expansion can also cause  
61 changes to major bio-geochemical cycles, soil properties and eco-hydrological processes (Pellis et al. 2019),  
62 loss of biodiversity especially in semi-open areas with species-rich grasslands, and loss of cultural  
63 landscapes (Otero et al. 2015; Hermoso et al. 2018; Ridding et al. in press). Secondary succession processes  
64 can result in multiple pathways and abandoned lands may become more vulnerable to invasive species and  
65 fire (Munroe et al. 2013).

66 For thousands of years, anthropogenic pressure over the Mediterranean basin has shaped the numerous  
67 and diverse cultural landscapes (Naveh 1995). In many European rural areas abandonment after WW2 was  
68 a widespread socio-economic process, causing large human migrations toward urban areas (MacDonald et  
69 al. 2000; Poyatos 2003; Hocht et al. 2005). The decline of traditional agro-pastoral activities was  
70 particularly intense in southern European mountains such as the Italian Alps and the Apennines. These two  
71 mountain ranges, covering approximately 35% of the entire country of Italy (Vacchiano et al. 2017),  
72 experienced a significant forest expansion after an extensive decrease of cultivated lands due to  
73 depopulation (Falcucci et al. 2007). Forest cover in Italy shifted from 6 million ha in 1936 (Forest Map of the  
74 Italian Kingdom) to 8.5 million ha in 1985 (First Italian Forest Inventory, IFNI85), and to 10.5 million in 2005  
75 (Second Italian Forest Inventory, INFC05) and is currently estimated at about 11 million ha in 2015 with an  
76 increase of 20% in the last 30 years (Ferretti et al. 2018). **These estimates rely on a wide range of sources,  
77 and studies using consistent datasets to quantify changes in land cover across broad areas prior to  
78 widespread availability of satellite imagery are lacking.** In the Italian and French Alps, the depopulation of  
79 marginal lands started after the Industrial Revolution in approximately 1871 and, due to the two World  
80 Wars, lasted through the 1950s (Batzing et al. 1996). Before the 1950s, grazing was widely distributed in  
81 the Italian Alps where rangelands occupied 53% of the mountain areas (White 1950; Garbarino et al. 2013).  
82 This was primarily cattle grazing in unfenced pastures. In the Apennines a human migration from mountain  
83 areas toward the Adriatic and Tyrrhenian coastal areas occurred from 1951 to 1991, especially in the  
84 northern and southern Apennines (Malandra et al. 2018; Vitali et al. 2018). Many of these areas were  
85 subjected to former heavy exploitation for firewood and charcoal production, with wood pastures  
86 occurring frequently at higher elevations. A national reforestation program to reduce slope erosion,  
87 launched before WW2 and lasting until the 1970s, resulted in approximately 760,000 ha of new plantation  
88 forests composed mainly of coniferous tree species (Piermattei et al. 2016).

89 In both mountain regions, forest expansion has occurred as a gap-filling process at lower elevations and as  
90 an upward shift of treeline at higher elevations (Tasser et al. 2005). Forest expansion caused a direct

91 reduction of open areas, reduced the extent of forest-grassland ecotones, and led to decreases in species  
92 diversity as well as culturally important landscapes (Falcucci et al. 2007; Petanidou et al. 2008). However,  
93 there are fundamental differences in how forest expansion processes have unfolded in the two mountain  
94 regions. A gentler topography and a favorable climate led to more intense deforestation in the Apennines,  
95 creating open areas that were used as pastures and crops both at low and high elevations. However,  
96 landscape mosaic simplification due to forest gap-filling processes mainly occurred at lower elevations. At  
97 higher elevations, forest succession on abandoned croplands and grasslands led to a complex and  
98 fragmented landscape (Malandra et al. 2019; Vitali et al. 2019). Understanding the underlying drivers of  
99 forest landscape changes by comparing the different land use legacies of the Alps and the Apennines is a  
100 fundamental step for more ecologically based landscape planning and management oriented toward  
101 biodiversity conservation and other ecosystem services.

102 The Alps and the Apennines are large and highly representative areas for testing our three hypotheses on  
103 mountain forest landscape changes in Italy over the last 60 years: 1) forest cover is increasing everywhere,  
104 but with different patterns in the Alps and the Apennines; 2) pasture-to-forest is the dominant landscape  
105 transition at high elevation; 3) historical forest cover (i.e. land use legacy) is the most important  
106 environmental driver for predicting forest expansion today.

107

## 108 **Methods**

### 109 *Study area and sampling design*

110 Our multiscale research design was structured at two spatial scales (region and landscape) aimed at  
111 comparing the two mountain ranges of Italy, the Alps (AL) and the Apennines (AP). They have similar total  
112 length (1300 – 1350 km, respectively), but different geographic orientation (AL: from west-to-east across  
113 northern Italy; AP: northwest-to-southeast from Liguria to Calabria). The two mountain ranges differ in  
114 terms of climate, topography and land use history.

115 In AL, mean annual temperatures range from less than 0° to over 10° C, with very cold winters. Annual  
116 precipitation ranges from 400 to over 3000 mm and summer dry periods are very rare (Isotta et al. 2013).  
117 Metamorphic lithology with intrusive igneous rocks prevail in the inner sectors and sedimentary outcrops  
118 dominate in the outer ones. Oak forests dominate at lower elevations whereas beech-silver fir (*Fagus*  
119 *sylvatica* and *Abies alba*) forests prevail on mesic aspects of the montane zone, replaced by *Pinus sylvestris*  
120 on xeric slopes. Coniferous forests with *Picea abies* (L.) H.Karst., *Larix decidua* Mill. and *Pinus cembra* L.  
121 dominate the subalpine zone (Fauquette et al. 2018).

122 At AP, mean annual temperatures range from 6° to 10° C, and annual precipitation ranges from 730 to 877  
123 mm, with a short and pronounced summer dry period at lower elevations (Blasi et al. 2014). The eastern  
124 Mediterranean side (Adriatic) is generally more continental and humid than the western (Tyrrhenian) one.  
125 The forest vegetation is largely dominated by broadleaf species of the Mediterranean and temperate  
126 biomes. Xeric oak forests of *Quercus ilex* L., *Quercus pubescens* Willd., *Quercus cerris* L. and *Ostrya*  
127 *carpinifolia* Scop. dominate at lower elevations and *Castanea sativa* Mill. the sub-montane zone. *Fagus*  
128 *sylvatica*, locally mixed with *Abies alba*, largely dominates the montane zone up to treeline except for a few  
129 locations in the central and southern sectors where natural pine forests occur, dominated by *Pinus mugo*,  
130 *P. heldreichii*, or *P. nigra laricio*.

131 For our regional scale analyses, the study area in each mountain chain included all contiguous land above  
132 500 m a.s.l. excluding those island polygons separated from the main mountain chains (Fig. 1). We obtained  
133 two large areas of 52,002 km<sup>2</sup> (AL) and 44,615 km<sup>2</sup> (AP), where we assessed the land-cover changes (LCC)  
134 for the 1990 – 2018 period, based on the Corine Land Cover (CLC Level 3, Feranec et al. 2016) raster maps

135 (100-m spatial resolution) after merging the original CLC categories into five larger groups: forest (FO),  
136 grassland (GR), cropland (CR), urban (UR), and unvegetated (UV) (Table S1). We developed a transition  
137 matrix for both regions by assessing changes for the five selected land-cover categories, allowing us to  
138 compute the relative changes in AL and AP.

139 For our landscape-scale analyses, in each region (AL and AP) we selected 8 landscapes of variable extent  
140 ranging from 6.3 to 16 km<sup>2</sup>. These landscapes were selected and harmonized from previous projects and  
141 unpublished data on land-use/land-cover changes in AL and AP (e.g. Garbarino et al. 2013; Malandra et al.  
142 2019). The 16 study landscapes cover a total surface area of approximately 23,000 ha within an elevation  
143 range of 500 – 2,600 m a.s.l., including all vegetation zones (Table 1). We adopted the altitudinal threshold  
144 of 2,600 m a.s.l., as the potential alpine treeline (Caccianiga et al. 2008; Lingua et al. 2008; Garbarino et al.  
145 2013) in order to limit the LUC analysis to the vegetated part of the 16 landscapes and to reduce the weight  
146 of the ‘rock’ land cover category, which is uninformative for our research. Historical aerial photographs for  
147 the years 1954-1962 (b/w, 1: 60,000 approximate cartographic scale, Italian Geographic Military Institute -  
148 IGMI) were scanned and digitized at 800 ppi, with a mean spatial resolution of 1 m. The IGMI images were  
149 georeferenced and orthorectified using PCI Geomatica 2012 software. Regularly distributed tie points were  
150 used to co-register IGMI images with 2012 orthophotos (RGB, 0.5 m cell size, National Agency for Funding  
151 in Agriculture - AGEA) resampled at 1 m. The average horizontal Root Mean Square Error (RMSE) was 23 m ±  
152 2SD. We used the TINITALY DEM at 10 m spatial resolution (Tarquini et al. 2012) for orthorectification.

153 We applied a semi-automated object-based classification by combining the automated image segmentation  
154 from eCognition software (scale factor 100, color factor 0.5) with on-screen photointerpretation of  
155 segmented polygons (Garbarino et al. 2013). We then performed a supervised classification of the objects  
156 based on an initial set of at least 10 training polygons for each category, selected through  
157 photointerpretation. This was followed by a manual classification of the previously unclassified polygons.  
158 Each polygon of the 32 land cover maps (16 landscapes × two time periods), was classified into five land  
159 cover classes that were used for the regional-scale analysis: forest (FO), grassland (GR), cropland (CR),  
160 urban (UR), unvegetated (UV). The UV category includes different land cover types such as rock, gravel,  
161 sand, bare soil and sparse vegetation areas. The latter is a mosaic of sparse grasslands and barren  
162 nonvegetated areas that are mostly located between 2000-3000 m a.s.l. A post-processing procedure on  
163 the resulting 32 land cover maps was performed in a GIS environment to enforce consistency among the  
164 two datasets. A minimum mapping unit (MMU) of 100 m<sup>2</sup> (Garbarino et al. 2011) was obtained by merging  
165 smaller polygons with neighboring larger ones by using the ArcGIS tool ‘Eliminate’ (Malandra et al. 2019).  
166 Merged polygons were rasterized at 1-m resolution and the resulting raster maps were smoothed using a  
167 moving window (3 × 3) majority filter. We obtained the level of accuracy by randomizing 16 polygons/ha on  
168 each map and classifying the objects visually using the same land cover categories adopted in the  
169 automatic segmentation (Radoux and Bogaert 2017). Overall, the classification accuracy ranged from 78%  
170 to 96% with a Cohen's Kappa coefficient between 0.67 and 0.93 (Table S2). The land cover change analysis  
171 at the landscape scale provided 16 transition matrices that were combined to detect overall transitions and  
172 differences between the AL and AP mountain regions. We converted the two transition matrices into two  
173 transition diagrams showing gain, loss, net change and persistence for each land cover category (Cousins  
174 2001). With the same dataset (Garbarino et al. 2019), we computed the relative contribution (in hectares)  
175 of each land cover category to the transition to forest cover and we applied a Mann–Whitney test to  
176 compare the medians of the two mountain ranges (AL and AP). The Mann–Whitney test was performed for  
177 each of the five categories by using the 8 landscapes as sample size for each mountain range.

178 For our landscape-scale analyses, we assessed the main drivers affecting forest expansion in AL and AP  
179 using a Random Forest (RF) model (Rodman et al. 2019). Specifically, we modelled the occurrence of a  
180 transition to forest through a binary classification method using ‘mlr’ (Bischi et al. 2016) and ‘ranger’  
181 (Wright & Ziegler 2017) R packages (R Core Team 2019). Given the unbalanced ratio between cells with a

182 transition to forest (minority class) and cells that remained unchanged (the majority class), we under-  
183 sampled unchanged cells using a spatially random selection within each landscape using the 'spatialEco' R  
184 package (Evans 2019). Before computing class transitions, we filtered out from the dataset the landscape  
185 portions that were already forests in the past, and we downscaled gridded land cover maps from 1 m to 30  
186 and 60 m resolutions using the majority class within each coarser cell. The coarser resolutions allowed us to  
187 limit the influence of both co-registration and classification errors of aerial images on model predictions  
188 and to evaluate the dependence of model predictions on the spatial scale. For our final analysis, we used  
189 the 30 m resolution because RF models trained with data at 30 or 60 m resolutions produced very similar  
190 outputs in terms of variables importance and trends of partial dependences. At a coarser resolution  
191 prediction errors slightly increased (Table S3).

192



193

194 Figure 1. Location of the 16 landscapes (white circles) within the two Italian mountain regions: the Alps (light green)  
195 and the Apennines (light grey) with a minimum elevation of 500 m a.s.l. For landscape codes see Table 1.

196

197 Because there was a substantial area of *Pinus* plantations within the forest cover of 2012 images in certain  
198 landscapes of the Apennines, we removed plantation patches before computing class transitions in order to  
199 model only natural forest dynamics.

200

201 Table 1. Environmental descriptors (Area = total surface area; El = mean elevation; Sl = mean slope; Te = mean annual  
 202 temperature; Pr = mean annual precipitations; BD = mean distance from buildings; RD = mean distance from roads) of  
 203 16 landscapes divided by mountain region (AL or AP).

Region	Landscape name	Landscape Code	Area (ha)	El (m a.s.l.)	Sl (°)	Te (°C)	Pr (mm)	BD (m)	RD (m)
AL	Bagni	BAN	1574.3	1788.1	36.0	3.9	1081.3	678.4	289.4
AL	Mello	MEL	1433.7	2045.8	34.1	1.7	983.7	935.0	359.8
AL	Sapè	SAP	959.4	1419.8	22.3	6.2	1001.9	343.8	178.4
AL	Pesio	PES	1599.2	1596.5	31.7	5.7	980.0	711.0	202.1
AL	Ventina	VEN	630.4	2248.6	30.1	0.1	900.8	1044.9	366.4
AL	Musella	MUS	921.4	2155.6	27.7	2.0	788.2	592.1	190.6
AL	Veglia	VEG	1407.2	2043.8	25.4	1.7	1045.1	815.3	205.1
AL	Devero	DEV	1570.0	2169.9	23.6	1.2	1138.6	1048.2	323.3
AP	Cimone	CIM	1593.4	1444.7	19.2	6.8	1352.5	349.3	111.6
AP	Sibillini	SIB	1601.3	1397.2	26.3	6.8	940.1	549.4	115.9
AP	Gran Sasso	GRS	1602.4	1577.5	27.2	6.3	872.3	1548.4	294.2
AP	Terminillo	TER	1600.7	1573.5	25.7	6.8	831.5	700.4	202.8
AP	Morrone	MOR	1603.7	1422.8	22.8	7.6	792.4	1447.3	276.9
AP	Genzana	GEN	1603.4	1234.7	22.4	8.2	789.1	664.7	228.5
AP	Monte Mare	MMA	1604.0	1149.7	24.1	9.0	780.9	1622.2	410.9
AP	Matese	MAT	1605.4	1112.5	22.5	9.2	694.7	481.4	163.4

204

205 We used several spatial predictors (Table S4) such as the distance from pre-existing forest edges,  
 206 topographic variables (elevation, slope, heat load index *sensu* McCune and Grace 2002), climatic variables  
 207 (mean annual temperature, annual precipitation), and anthropogenic variables (cost of movement,  
 208 Euclidean distance to buildings, Euclidean distance to roads). We derived topographic variables from the 10  
 209 m DEM and climatic variables from the ‘Climatologies at high resolution for the earth’s land surface areas’  
 210 (CHELSA) v1.2 datasets at 30 arcsec (~1 km) spatial resolution (Karger et al. 2017). We computed the  
 211 accumulated cost of movement across the terrain through the Tobler’s hiking function (on-path)  
 212 implemented in the ‘movecost’ R package (Alberti 2019), using “buildings” in OpenStreetMap as starting  
 213 locations. We applied two different approaches to obtain either the RF models predictions or the predictive  
 214 performance estimates with a reduced bias. Specifically, we trained two RF models, one for AL and one for  
 215 AP, using all the data and tuning hyper-parameters through an 8-fold spatial cross-validation (Brenning  
 216 2012, Schratz et al. 2019). We used bias-reduced predictive performance estimates using two common  
 217 measures in binary classification, the Brier score (Brier 1950) and the area under the receiver operating  
 218 characteristics curve (AUC). These measures were averaged over a total of 800 RF models obtained through  
 219 an 8-fold spatial cross-validation repeated 100 times using a nested 5-fold spatial cross-validation for  
 220 hyper-parameters tuning (Lovelace et al. 2019, Schratz et al. 2019). For both strategies, we used a  
 221 sequential model-based optimization approach in ‘mlrMBO’ R package (Bischl et al. 2017) to search for the  
 222 optimal RF hyper-parameters (mtry, sample fraction and minimum node size) using 50 steps. The spatial  
 223 cross-validation resampling technique was based on k-means clustering of observation coordinates and  
 224 allowed us to geographically partition the data, thus maintaining the assumption of independence among  
 225 training and test sets which would be violated in the case of randomly sampled observations due to the  
 226 presence of spatial autocorrelation. We assessed variable importance from each model using the  
 227 permutation method (Breiman 2001) and we employed partial dependencies (Friedman 2001; Goldstein et  
 228 al. 2015) to interpret the marginal effect of each variable on the predicted probability of forest expansion.  
 229 Specifically, we computed the average and the standard deviation of individual marginal effects obtained  
 230 using all the observations in the dataset through the ‘generatePartialDependenceData’ function in ‘mlr’ R  
 231 package.  
 232  
 233  
 234  
 235

236 **Results**

237 *Regional land cover changes – CORINE database*

238 Forest expansion occurred in both areas, but was greater in AL (+2,951 ha, +9 %) than in AP (+1023 ha, +3.7  
 239 %) (Tab. 2). Cropland cover is generally stable whereas human infrastructures increased more at AP (+ 131  
 240 ha, +34 %) than at AL (+256 ha, +19 %). Grasslands greatly decreased at both mountain ranges, but more at  
 241 AL (-2784 ha, -39 %) than at AP (-1160 ha, -27 %), a pattern also observed for unvegetated areas (AP -56 ha,  
 242 -19 %; AL -503ha, -9 %). Regional scale results (1990-2018) were weakly in agreement with the landscape  
 243 scale results (1954-2012) as shown in the supplementary material (Table S5).

244

245 Table 2. Land cover categories surface areas expressed as a percentage of the total mountain area derived from the  
 246 Corine Land Cover in the Alps (AL) and the Apennines (AP) throughout the years. Changes across the entire period  
 247 (1990-2018) are indicated in the last two columns as absolute and relative percent values.

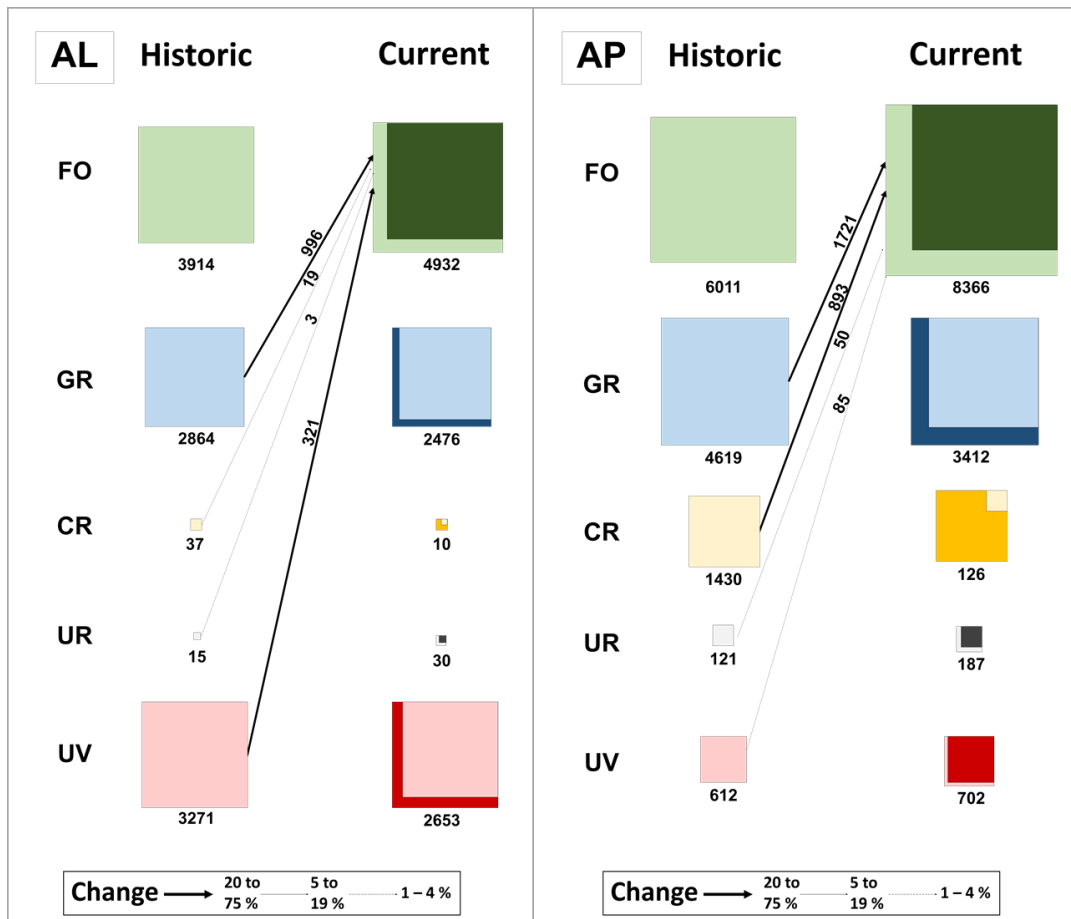
AL	1990	2000	2006	2012	2018	1990-2018 Change	
						Absolute	Relative
Forest (FO)	62.9	62.4	62.5	68.6	68.6	+5.7	+9.0
Grassland (GR)	13.8	14.9	14.6	8.5	8.5	-5.4	-38.8
Cropland (CR)	10.1	10.1	10.4	10.2	10.2	+0.2	+1.5
Urban (UR)	2.6	2.7	2.8	3.0	3.1	+0.5	+19.3
Unvegetated (UV)	10.6	9.9	9.7	9.6	9.6	-1.0	-9.2
AP	1990	2000	2006	2012	2018	1990-2018 Change	
						Absolute	Relative
Forest (FO)	62.5	62.5	62.3	64.8	64.8	+2.3	+3.7
Grassland (GR)	9.8	9.8	9.8	7.2	7.2	-2.6	-26.6
Cropland (CR)	26.2	26.1	26.2	26.3	26.3	+0.1	+0.5
Urban (UR)	0.9	1.0	1.1	1.1	1.2	+0.3	+34.2
Unvegetated (UV)	0.7	0.6	0.5	0.5	0.5	-0.1	-19.1

248

249 *Landscape transitions – aerial imagery*

250 Forest expansion also occurred at the landscape scale in both ranges. For all study landscapes combined,  
 251 the mean annual forest surface area increment was 60 ha/year (0.5 %/year), and was slightly greater at AP  
 252 (41 ha yr<sup>-1</sup> or 0.6% yr<sup>-1</sup>) than at AL (19 ha yr<sup>-1</sup> or 0.4% yr<sup>-1</sup>). Grasslands and Crops decreased in both areas,  
 253 but a larger reduction of crops (CR) occurred at AP (Fig. 2). Unvegetated lands (UV) decreased only at AL,  
 254 and urban infrastructures (UR) increased more at AP. The relative weights of CR and UR were historically  
 255 higher at AP, whereas UV values were historically higher at AL. Forest expansion was mostly related to the  
 256 “GR to FO” transition (66.3 % overall), but was greater at AL than at AP (74.4 % and 62.4 % respectively, Fig.  
 257 3). The “CR to FO” transition was stronger at AP than AL (32.4 % and 1.4 %), whereas the opposite pattern  
 258 was observed for the “UV to FO” transition (AL = 23.9 %, AP = 3.1 %). All land cover transitions to forest  
 259 were significantly different between the two mountain ranges (Mann-Whitney test: GR, UR with  $p < 0.05$ ;  
 260 CR, UR with  $p < 0.01$ ).

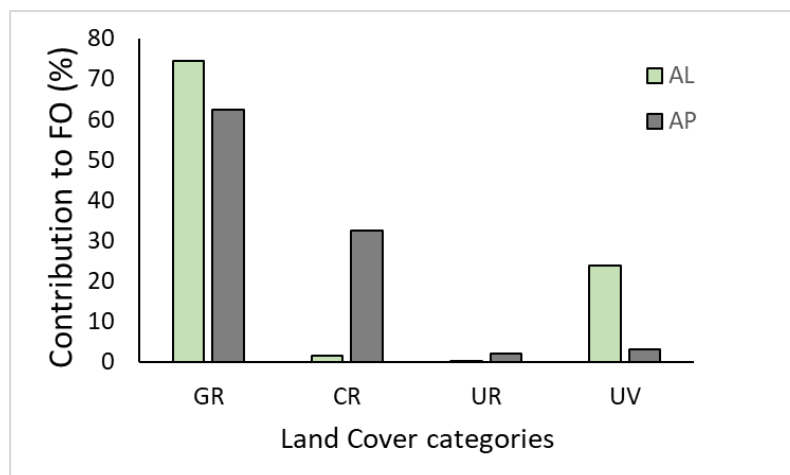
261



262

263 Figure 2. Area of land cover classes (ha) and land cover transitions from historic (1954-1962) to present time (2012) in  
 264 the Alps (left panel) and the Apennines (right panel) study sites. Colored boxes refer to land cover categories with box  
 265 size scaled to area: darker-colored inset boxes represent land cover class (LCC) persistence over time in the case of  
 266 LCC increase (e.g. FO and UR categories); light-colored inset boxes represent persistence over time in the case of LCC  
 267 decrease (e.g. GR, CR and UV). Transitions representing forest expansion are highlighted with arrows. Arrow thickness  
 268 increases with magnitude of the land cover transition. The area converted to forest (ha) for each transition is reported  
 269 in text above the arrow symbols.

270



271

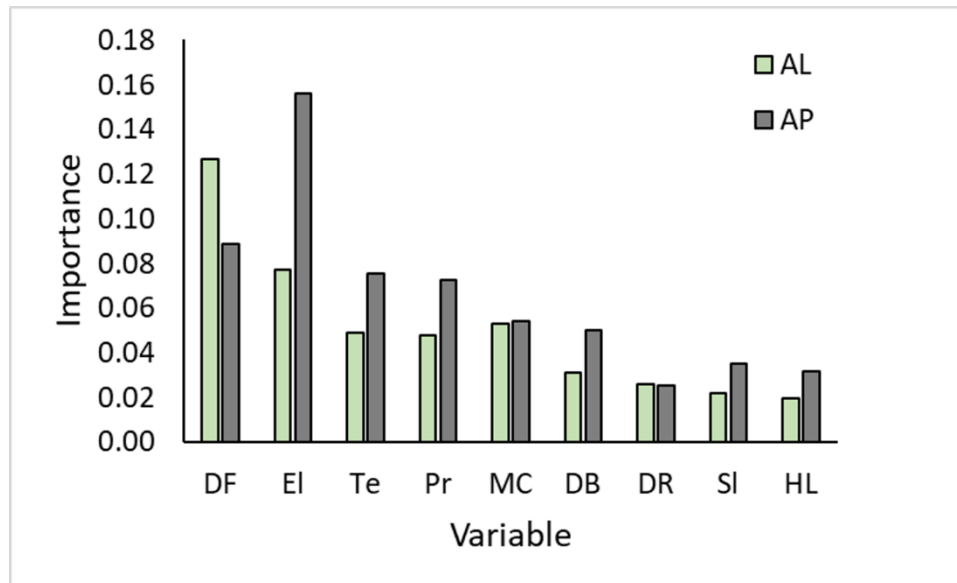
272 Figure 3. Percent contribution of each land cover category (GR = grassland, CR = cropland, UR = urban, UV =  
 273 unvegetated) to forest expansion over the studied period (1954-2012).

274

275 *Drivers of forest expansion*

276 RF models derived for the forest expansion portion of the landscape indicate that the best predictor was  
277 the distance from pre-existing forest edges (DF), particularly at AL (importance rate -  $IR = 0.13$ , Fig. 4).  
278 Forest expansion is predicted also by elevation (EI), which is particularly important for AP mountain range  
279 (AL:  $IR = 0.08$ , AP:  $IR = 0.16$ ). Climatic variables such as mean annual temperature (Te) and precipitation (Pr)  
280 were more important at AP ( $IR = 0.07-0.08$ ). Anthropogenic impact proxy variables (MC, DB and DR) were  
281 less influential in the models ( $IR = 0.05-0.03$ ), but DB was more important for AP than for AL ( $IR = 0.05$  and  
282 0.03 respectively).

283

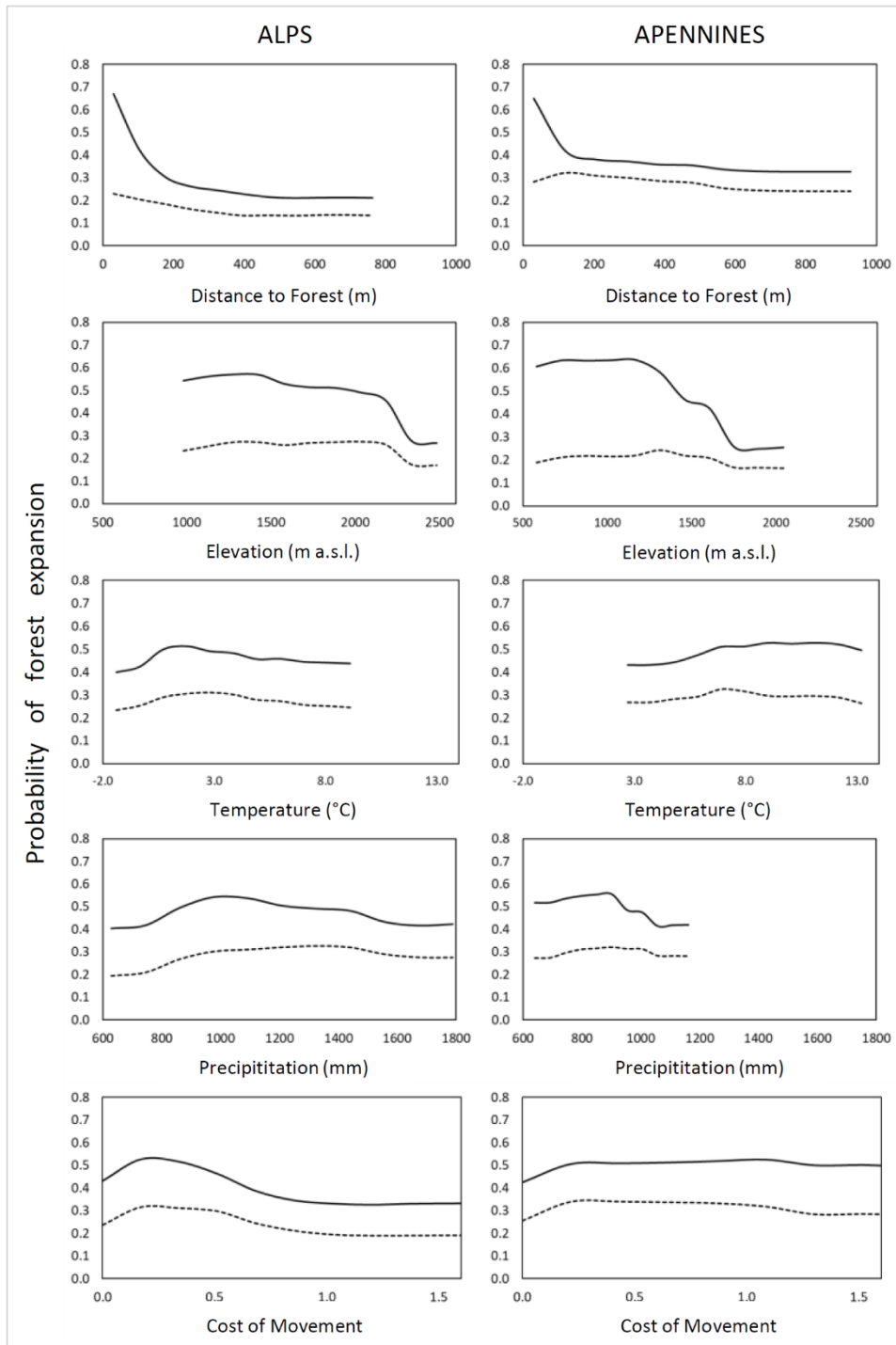


284

285 **Figure 4.** Importance rate of variables in random forest (RF) models of the Alps (light green) and the Apennines (grey).  
286 Variables are: distance from pre-existing forest edges (DF), topographic (EI = elevation, SI = slope, HL = Heat load  
287 index), climatic (Te = mean annual temperature, Pr = annual precipitation) and anthropogenic (MC = cost of  
288 movement, DB = Euclidean distance to buildings, DR = Euclidean distance to roads).

289

290 At AL forest expansion probability was higher close to pre-existing forest edges, rapidly declining between 0  
291 and 200 m and with a gradual decline between 200 and 800 m (Fig. 5). At AP the negative relationship  
292 between forest expansion probability and distance to pre-existing forest edges featured a rapid decline  
293 (from 0.6 to 0.4 of probability) between 0 and 150 m and a gradual decline between 150 and 900 m. The  
294 effect of distance from pre-existing forest edges (DF) observed at AP exhibited a higher heterogeneity  
295 compared to those observed at AL as highlighted by standard deviation computed at different values of the  
296 predictor variable (Fig. 5). Forest expansion at AP was more likely to occur at lower elevations (500 – 1,000  
297 m a.s.l.) and the probability abruptly decreased between 1,000 and 1,500 m a.s.l. A similar pattern was  
298 observed at AL, but at higher elevations (1,000 – 2,000 m a.s.l.), with a clear decrease from 2,000-2,500 m  
299 a.s.l. Relationships between forest expansion probability and annual temperature were generally weak,  
300 although there was a slightly higher probability of forest expansion occurring between 2.5 - 7 °C at AL and  
301 7.5 - 13 °C at AP.



302

303 Figure 5. Partial dependence plots showing relative influences of the **five most important predictors** on the probability  
 304 of forest expansion, for the Alps **(left)** and the Apennines **(right)** across the respective input data ranges. **We used all**  
 305 **observations** to train the model for computing the partial dependence function. Solid lines indicate the average over  
 306 individual marginal effects of each selected explanatory variable (distance from pre-existing forest edges, elevation,  
 307 temperature, **precipitation** and cost of movement) whereas dotted lines **are the** standard deviations of individual  
 308 marginal effects.

309

310

311

## 312 Discussion

313 Forest expansion following land abandonment is a well-known process in mountain forests globally (Sitzia  
314 et al. 2010). For example, forest expansion in mountainous populated areas has been recently detected in  
315 South America (Nanni et al. 2019) and East Asia (Fang et al. 2014). Grazing decline and fire suppression  
316 favored forest expansion and forest infilling in California, USA (Lydersen and Collins 2018) and recently rain  
317 forest expansion into savanna has been detected in Australia (Ondei et al. 2017). Natural forest expansion  
318 is particularly evident and rapid in several mountain ranges of the World such as in the Mediterranean  
319 Basin (e.g. Roura-Pascual et al. 2005; Niedrist et al. 2009; Weisberg et al. 2013) where agro-silvo-pastoral  
320 traditional practices declined abruptly due to rural depopulation (Lasanta et al. 2017). However, there have  
321 been few studies comparing post-abandonment forest expansion patterns among different regions or  
322 mountain ranges (e.g. Tasser et al. 2007; Fontana et al. 2014).

323 By comparing the Italian Alps and the Apennines we found that environmental influences on forest  
324 expansion processes were similar between the two regions. Our results for the observed time span (1954-  
325 2012) indicate an overall forest area increase of 0.6% yr<sup>-1</sup> in the Italian Alps and Apennines. These values  
326 match with the annual increments recently reported either for the entire Italian peninsula in 1985-2005  
327 (0.3% yr<sup>-1</sup>) and 2005-2015 (0.2% yr<sup>-1</sup>) periods (RAF 2018) or for different sites of the Apennines (0.4 - 0.7%  
328 yr<sup>-1</sup>, Brachetti et al. 2012; Malandra et al. 2019). Similar rates are reported for other Alpine regions such as  
329 Carnia (0.7% yr<sup>-1</sup>), Tyrol (0.35% yr<sup>-1</sup>) and South Tyrol (0.1% yr<sup>-1</sup>) in the 1955-2000 period (Tasser et al. 2007).

330 Important differences between the two studied mountain ranges emerged from our analysis. Forest  
331 expansion was more intense in the Apennines during the 1954-2012 period. This outcome could be related  
332 to the different geographic layout of this mountain range and the wider latitudinal gradient that it  
333 encompasses, providing warmer climate conditions more favorable for forest regeneration. Another  
334 possible explanation for this pattern arises from the large differences in elevation gradients between the  
335 two mountain ranges. Abandoned sites at lower elevations that were previously cultivated or grazed were  
336 more common in the Apennines than in the Alps, and such sites experienced more rapid and extensive  
337 forest expansion.

338 These differences highlight the importance of regional variation in climate and land use history for  
339 understanding and predicting forest landscape change following agricultural abandonment. Differences in  
340 land use history expressed by a mosaic of former croplands and pastures have important long-term  
341 implications for post-abandonment forest establishment (Zimmermann et al. 2010). At the regional scale,  
342 we found a greater reduction of grasslands in the Alps than in the Apennines, where we found a greater  
343 increase of anthropogenic land cover types (mostly UR). The landscape transitions from grasslands,  
344 croplands, and unvegetated lands to forests were by far the most relevant at our landscape scale of  
345 analysis. Grassland-to-forest was the dominant shift in both mountain ranges due to a general decline of  
346 traditional cattle grazing in mountain areas (e.g. Nagy et al. 2003). However, the two mountain ranges  
347 differ in that the widespread transition from unvegetated areas (e.g. rocks and bare soil) to forest occurred  
348 only in the Alps. Here, this transition is probably due to the tendency for coniferous treeline species (*Larix*  
349 *decidua* and *Pinus cembra*) to invade higher-elevation, shrub-dominated and alpine plant community types  
350 (Vittoz et al. 2008). On the other hand, *Fagus sylvatica* dominated treelines of the Apennines are less prone  
351 to upward migration; forest expansion here was mostly the outcome of gap infilling processes (Vitali et al.  
352 2018, Malandra et al. 2019). High elevation forests in the Apennines are dominated by *Fagus sylvatica*, a  
353 strongly resprouting species, but with heavy seeds that disperse predominantly over short distances (Vitali  
354 et al. 2017). Conifer species with greater long-distance seed dispersal ability occur at a few sites of the  
355 central (*Pinus nigra* – Vitali et al. 2017; *Pinus mugo* – Dai et al. 2017) and southern (*Pinus heldreichii* – Vitali  
356 et al. 2018) Apennines. Here, croplands-to-forest was the second most important transition, given the  
357 possibility of growing a few rare food crops (e.g. potatoes, special cultivars of cereals, apples and chestnuts)

358 at higher elevations especially on southern or less exposed slopes (Bracchetti et al. 2012; Rovelli 2019). The  
359 abandonment of upland traditional farming systems in the Apennines is one of the most important socio-  
360 economic drivers of landscape degradation and biodiversity depletion (Farina 1995; Zimmermann et al.  
361 2010).

362 Pre-existing forest edges emerged as a key land use legacy for future forest expansion both in the Alps  
363 (Abadie et al. 2017; Tasser et al. 2007) and the Apennines (Malandra et al. 2019) with a greater importance  
364 in the Alps. A general explanation for this is related to seed source availability and to the marginality of  
365 ecotones such as forest edges. These are the first pastoral zones to be abandoned when grazing pressure is  
366 reduced. The distance from pre-existing forest edges (years 1954-1962) appears a stronger driver in the  
367 Alps where, because of harsh conditions at higher elevations, favorable microsites are necessary for tree  
368 establishment. In the Apennines, where this variable was second in importance, high variability in effect  
369 size is likely caused by heterogeneity among individual observations belonging to different landscapes. On  
370 the other hand, in the Apennines, elevation was the most influential predictor variable with widespread  
371 forest expansion having occurred at lower altitudes on slopes severely exploited prior to the analyzed time  
372 span (1954-2012). The probability of forest expansion gradually decreased along an altitude gradient from  
373 1,000 to 1,800 m a.s.l. in the Apennines, but decreased abruptly between 2,000 and 2,300 m a.s.l. in the  
374 Alps. Forest expansion on former pastures and croplands was also faster at lower elevations in mountains  
375 of southern Spain (Fernández et al. 2004).

376 The importance of land use legacy for forest landscape dynamics is emphasized by long-term studies  
377 demonstrating that legacies may persist for decades, affecting current and future land cover changes  
378 (Loran et al. 2017; Tasser et al. 2017). Human activities such as harvesting, grazing, fire and litter removal  
379 when practiced for long time periods, may greatly affect current forest dynamics (Gimmi et al. 2013). The  
380 role of land use legacies on past and future forest dynamics is typical of many southern European mountain  
381 ranges shaped by historical anthropogenic disturbance regimes such as an intensive land use (Albert et al.  
382 2008; Ameztegui et al. 2016). Our study confirms the importance of the location of pre-existing forest  
383 edges as the legacy of centuries of human land use in mountain regions, as in other Mediterranean  
384 mountain ranges such as the Pyrenees and the French Alps (Mouillot et al. 2005; Gartzia et al. 2016; Abadie  
385 et al. 2017).

386 The differences observed in land cover change patterns between the Alps and the Apennines are not  
387 surprising because of strong regional differences in climate, geology, topography, vegetation (e.g. treeline  
388 species composition). Forest expansion by upward treeline rise or forest gap-filling processes has occurred  
389 primarily on warmer and gentler slopes (e.g. southern exposure), whether in the Alps (Tasser et al. 2007;  
390 Garbarino et al. 2013), the Apennines (Vitali et al. 2018) or the Pyrenees (Gartzia et al. 2016). More  
391 favorable climate conditions and the greater availability of abandoned open areas make south-exposed low  
392 elevation sites suitable areas for forest expansion. Ultimately, the more rapid rate of forest expansion in  
393 the Apennines was linked to the greater availability of open areas given the more intense previous land  
394 use. Tree encroachment on old pastures by secondary succession and on former unvegetated areas  
395 through primary succession prevail in the Alpine region where climate change appears to have a strong  
396 influence (Dirnböck et al. 2003; Gehrig-Fasel et al. 2007; Giorgi and Lionello 2008). Elevation plays a  
397 fundamental role on forest dynamics at both landscape and stand scales in the Alps (Garbarino et al. 2009;  
398 Kulakowski et al. 2011). Land use legacies such as conifer plantations and high elevation crop farming seem  
399 stronger in the Apennines where climate change effects on forest expansion at high elevation appear  
400 constrained by the unsuitability of *Fagus sylvatica* to migrate upwards due to its heavy seeds and its limited  
401 ability to invade adjacent plant community types (Vitali et al. 2018, 2019). However, the limited transitions  
402 from unvegetated areas to forests in the Apennines were also due to a combination of topographic  
403 influences and the previous land use. In particular, several Apennines peaks with sandy or marl-sandy soils

404 are less topographically limited (mountain mass effect) so that unvegetated areas are rare and in the  
405 absence of past human activities they are climatically suitable for forest dominance.

406 Forest expansion is an emerging and debated issue that requires accurate measurement and monitoring to  
407 allow for proper management of current and future dynamics (Otero et al. 2015). There are two main  
408 management strategies: i) passive management to support rewilding processes and limit human induced  
409 landscape fragmentation and ii) active management to control and limit the negative effects of re-  
410 vegetation processes (Lasanta et al. 2015). Negative effects of natural forest expansion include  
411 simplification of landscape structure, decline of species diversity, increased risk of fire and soil erosion, and  
412 the loss of cultural landscapes (Lasanta et al. 2015; Ferretti et al. 2019). A balance between conservation  
413 through monitoring and active management of secondary succession dynamics (new forests) should be  
414 attempted. A recent review, contrasting active management strategies with passive strategies allowing  
415 forest secondary succession, found that the most efficient technique seems to be a combination of clearing  
416 and extensive grazing (Lasanta 2019), maintaining high levels of landscape complexity and forest-meadow  
417 edge.

418 With this study, by means of a standardized aerial image processing protocol we provided a robust dataset  
419 that should be implemented with more comprehensive records (Garbarino et al. 2019). Quantitative  
420 historical ecology with data on land use legacies can provide excellent information for ecosystem modelling  
421 to predict forest landscape changes (Stürck and Verburg 2017).

422 We have shown that forest expansion in mountain ranges of Italy is controlled by land use legacies of pre-  
423 existing forest edges, interacting with topography and climate. The Alps and the Apennines showed similar  
424 landscape changes featuring grassland-to-forest transitions. However, the rate of forest expansion was  
425 faster in the Apennines for the larger occurrence at lower elevations of old-fields recolonized by secondary  
426 forests. In the Alps, climate and land use changes favored a widespread transition from unvegetated areas  
427 to forest at higher elevations. Our results could be biased by the stronger mass effect on the Alps, and the  
428 higher average elevation of alpine landscapes. A further limit in our approach is the spatial resolution  
429 mismatch between the 1-km climate data resolution and the 30 m unit of forest expansion analysis. Thus,  
430 the influence of climatic variables on forest expansion could be underestimated by our random forest  
431 models.

432 Despite these limitations, our results demonstrate that post-abandonment forest expansion is a  
433 widespread and ongoing process in Italian mountain forest landscapes. Future research should increase the  
434 number of surveyed sites for increased sensitivity in comparing regional differences. It would be  
435 informative to apply a land use change modeling approach. Predicting new landscape scenarios for Italian  
436 mountain forests should account for the possible changes to disturbance regimes linked to climatic changes  
437 (Vacchiano et al. 2017). The extensive forest cover that is blanketing large mountain areas has important  
438 implications for habitat and biodiversity. Forest expansion in these mountain landscapes additionally leads  
439 to an increase of fuel load continuity that increases the risk of wildfires, particularly in areas exposed to  
440 severe drought stress increased by recent climate changes. Large wildfires have recently increased in  
441 occurrence in mountain areas where they have historically been quite rare due to the prevalence of  
442 managed pastures and farmlands. Other implications regard snowfall and accumulation regimes in  
443 combination with soil erosion dynamics after forest fire. These issues are connected also to the naturalness  
444 of these processes triggered by man in human-shaped landscapes. A no-management approach of the  
445 successional processes would not guarantee, at least in the short term, a strictly natural forest  
446 encroachment. A comprehensive overview and assessment of the multiple ecosystem services provided by  
447 these complex and millenary landscapes is necessary in order to attempt a sustainable forest management  
448 (Schulze and Schulze, 2010).

449

450 **Author contribution**

451 **Matteo Garbarino conceived the experiment and all authors contributed to the study design.** Material  
452 preparation, data collection and analysis were performed by Matteo Garbarino, Donato Morresi, Emanuele  
453 Sibona, Francesco Malandra, Alessandro Vitali **and Carlo Urbinati.** The first draft of the manuscript was  
454 written by Matteo Garbarino and all authors commented on previous versions of the manuscript. All  
455 authors read and approved the final manuscript.

456 **Data availability**

457 The datasets generated during and analyzed during the current study are available in the Figshare  
458 repository, <https://doi.org/10.6084/m9.figshare.11409444.v1>

459

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- 686

687 **Supplemental material**

688 Table S1. Harmonization details of the Corine Land Cover legend in 5 land cover categories at AL and AP.

Corine Land Cover		Harmonization	
Code	Description	Code	Description
111	Continuous urban fabric	UR	Urban
112	Discontinuous urban fabric	UR	Urban
121	Industrial or commercial units	UR	Urban
122	Road and rail networks and associated land	UR	Urban
123	Port areas	UR	Urban
124	Airports	UR	Urban
131	Mineral extraction sites	UR	Urban
132	Dump sites	UR	Urban
133	Construction sites	UR	Urban
141	Green urban areas	UR	Urban
142	Sport and leisure facilities	UR	Urban
211	Non-irrigated arable land	CR	Cropland
212	Permanently irrigated land	CR	Cropland
213	Rice fields	CR	Cropland
221	Vineyards	CR	Cropland
222	Fruit trees and berry plantations	CR	Cropland
223	Olive groves	CR	Cropland
231	Pastures	GR	Grassland
241	Annual crops associated with permanent crops	CR	Cropland
242	Complex cultivation patterns	CR	Cropland
243	Land principally occupied by agriculture with ... natural vegetation	CR	Cropland
244	Agro-forestry areas	CR	Cropland
311	Broad-leaved forest	FO	Forest
312	Coniferous forest	FO	Forest
313	Mixed forest	FO	Forest
321	Natural grasslands	GR	Grassland
322	Moors and heathland	FO	Forest
323	Sclerophyllous vegetation	FO	Forest
324	Transitional woodland-shrub	FO	Forest
331	Beaches dunes sands	UV	Unvegetated
332	Bare rocks	UV	Unvegetated
333	Sparsely vegetated areas	UV	Unvegetated
334	Burnt areas	FO	Forest
335	Glaciers and perpetual snow	UV	Unvegetated
411	Inland marshes	UV	Unvegetated
412	Peat bogs	UV	Unvegetated
421	Salt marshes	UV	Unvegetated
422	Salines	UV	Unvegetated
423	Intertidal flats	UV	Unvegetated
511	Water courses	UV	Unvegetated
512	Water bodies	UV	Unvegetated
521	Coastal lagoons	UV	Unvegetated
522	Estuaries	UV	Unvegetated
523	Sea and ocean	UV	Unvegetated
999	NODATA	999	No Data

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690 Table S2. Classification accuracy (OA = overall accuracy, K = Cohen's Kappa coefficient) of 32 land cover  
 691 maps (16 landscapes x 2 periods).

<b>Landscape</b>	<b>Year</b>	<b>OA</b>	<b>K</b>
BAG	1962	79	0.69
	2012	89	0.83
CIM	1954	82	0.73
	2012	93	0.88
DEV	1954	82	0.71
	2012	86	0.77
GEN	1954	78	0.70
	2012	78	0.67
GRS	1954	80	0.67
	2012	86	0.76
MAT	1954	86	0.77
	2012	94	0.88
MEL	1962	82	0.73
	2012	88	0.82
MMA	1954	91	0.83
	2012	90	0.68
MOR	1954	82	0.69
	2012	90	0.83
MUS	1961	82	0.72
	2012	89	0.84
PES	1954	88	0.78
	2012	86	0.73
SAP	1954	84	0.73
	2012	91	0.84
SIB	1954	86	0.80
	2012	86	0.77
TER	1954	85	0.75
	2012	84	0.71
VEG	1954	87	0.81
	2012	91	0.87
VEN	1961	94	0.89
	2012	96	0.93

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700 Table S3. Random forest model parameters used in this study (N transitions = number of forest expansion  
 701 pixels, N total = number of total pixels in the model, OOB = Out-of-bag error or prediction error of RF  
 702 models, Brier score = Brier predictive performance estimate, AUC = area under the receiver operating  
 703 characteristics curve, K = Cohen's Kappa coefficient) computed for the AL and the AP datasets both at 30  
 704 and 60 m spatial resolutions.

RF models	AL 30 m	AP 30 m	AL 60 m	AP 60 m
N transitions	14420	21027	3555	5184
N total	28900	40575	7082	10010
OOB	0.108	0.091	0.126	0.098
Brier score	0.175	0.151	0.182	0.132
AUC	0.829	0.854	0.819	0.849
K	0.482	0.519	0.483	0.510
DF IR	0.127	0.088	0.114	0.072
EI IR	0.077	0.156	0.065	0.168
MC IR	0.053	0.054	0.034	0.039
Te IR	0.049	0.076	0.033	0.051
Pr IR	0.048	0.073	0.028	0.060
DB IR	0.031	0.050	0.016	0.033
DR IR	0.026	0.025	0.014	0.012
SI IR	0.022	0.035	0.013	0.030
HL IR	0.019	0.032	0.011	0.023
Total IR	0.452	0.589	0.329	0.489

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707 Table S4. Description, data sources, spatial characteristics and usage rationale of explanatory and predictor  
 708 variables used in the Random Forest models.

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Variable	Code	Type	Resolution	Data source	Description
Forest expansion	FE	Binary	10 m	LC map	Transition to forest occurrence
Elevation	EI	Topographic	10 m	DEM tinality	Gradient of site suitability
Slope	SI	Topographic	10 m	DEM tinality	Proxy of human pressure
Heat Load Index	HL	Topographic	10 m	DEM tinality	Gradient of site suitability
Precipitation	Pr	Climatic	1 km	CHELSEA	Average annual precipitation
Temperature	Te	Climatic	1 km	CHELSEA	Average annual temperature
Distance to Forests	DF	LU Legacy	10 m	LU 1954	Distance to former forest borders
Distance to Roads	DR	Anthropic	10 m	OSM	Euclidean distance from roads
Distance to Buildings	DB	Anthropic	10 m	OSM	Euclidean distance from buildings
Moving cost	MC	Anthropic	10 m	DEM - OSM	Cost of movement across the terrain

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716 Table S5. Land cover surface as a percentage of the total surface of AL and AP landscapes (10091 and 12830  
717 ha, respectively) divided by regional (CORINE land cover) and landscape (aerial imagery) scales. For  
718 comparison purposes, the considered study area is included within the borders of the 16 selected  
719 landscapes.

Regional scale (CORINE LC)				Landscape (Aerial imagery)			
AL	1990	2018	Delta	AL	1954	2012	Delta
FO	51.58	53.02	1.44	FO	38.75	48.82	10.07
GR	16.16	4.43	-11.73	GR	28.35	24.51	-3.84
CR	0.81	0.55	-0.26	CR	0.37	0.10	-0.26
UR	0.04	0.04	0.00	UR	0.15	0.30	0.15
UV	31.40	41.96	10.55	UV	32.38	26.26	-6.11
AP	1990	2018	Delta	AP	1954	2012	Delta
FO	67.16	65.98	-1.18	FO	46.99	65.40	18.41
GR	16.03	10.82	-5.21	GR	36.11	26.67	-9.44
CR	3.52	3.66	0.14	CR	11.17	0.98	-10.19
UR	0.65	0.70	0.05	UR	0.95	1.47	0.52
UV	12.63	18.84	6.21	UV	4.78	5.49	0.70

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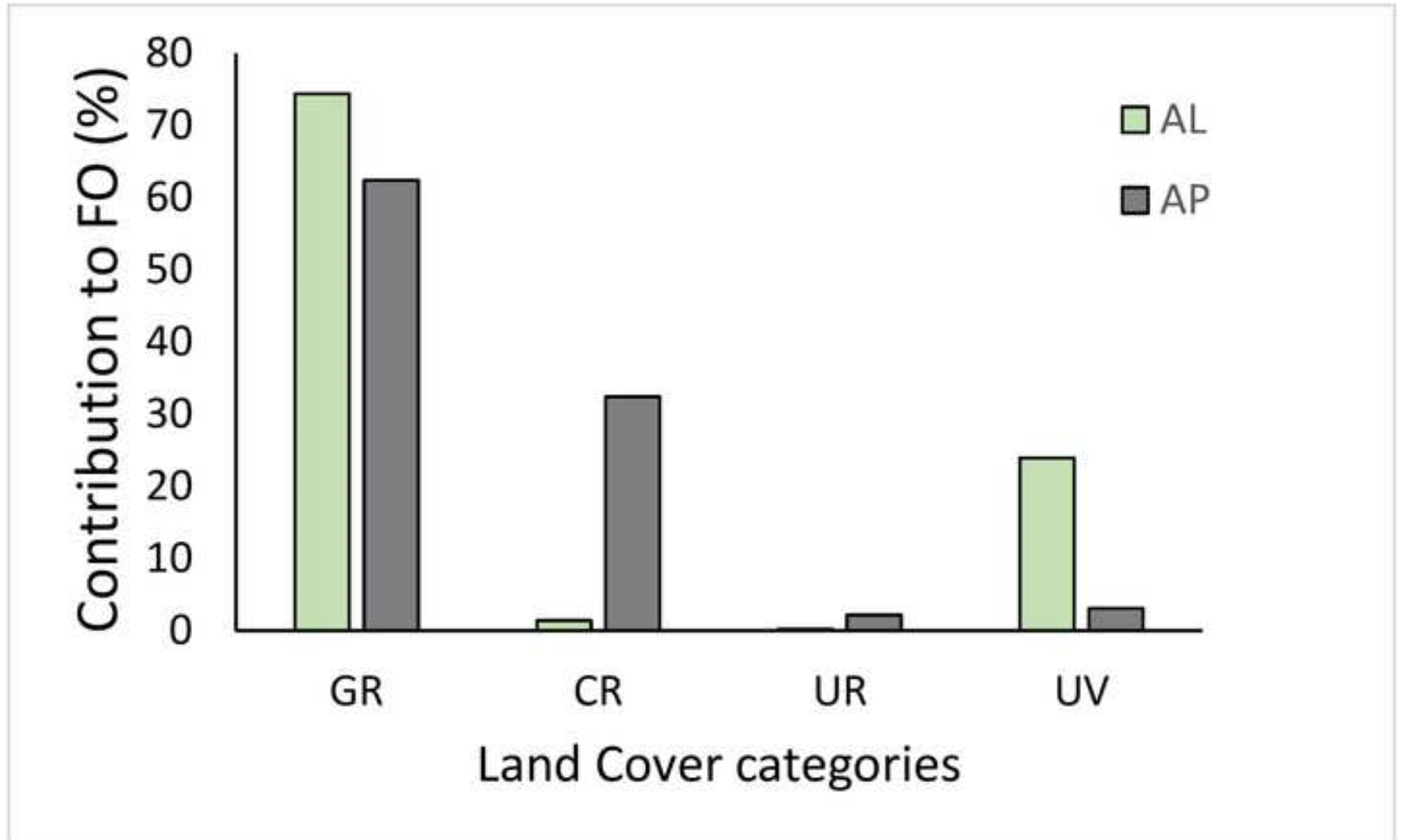
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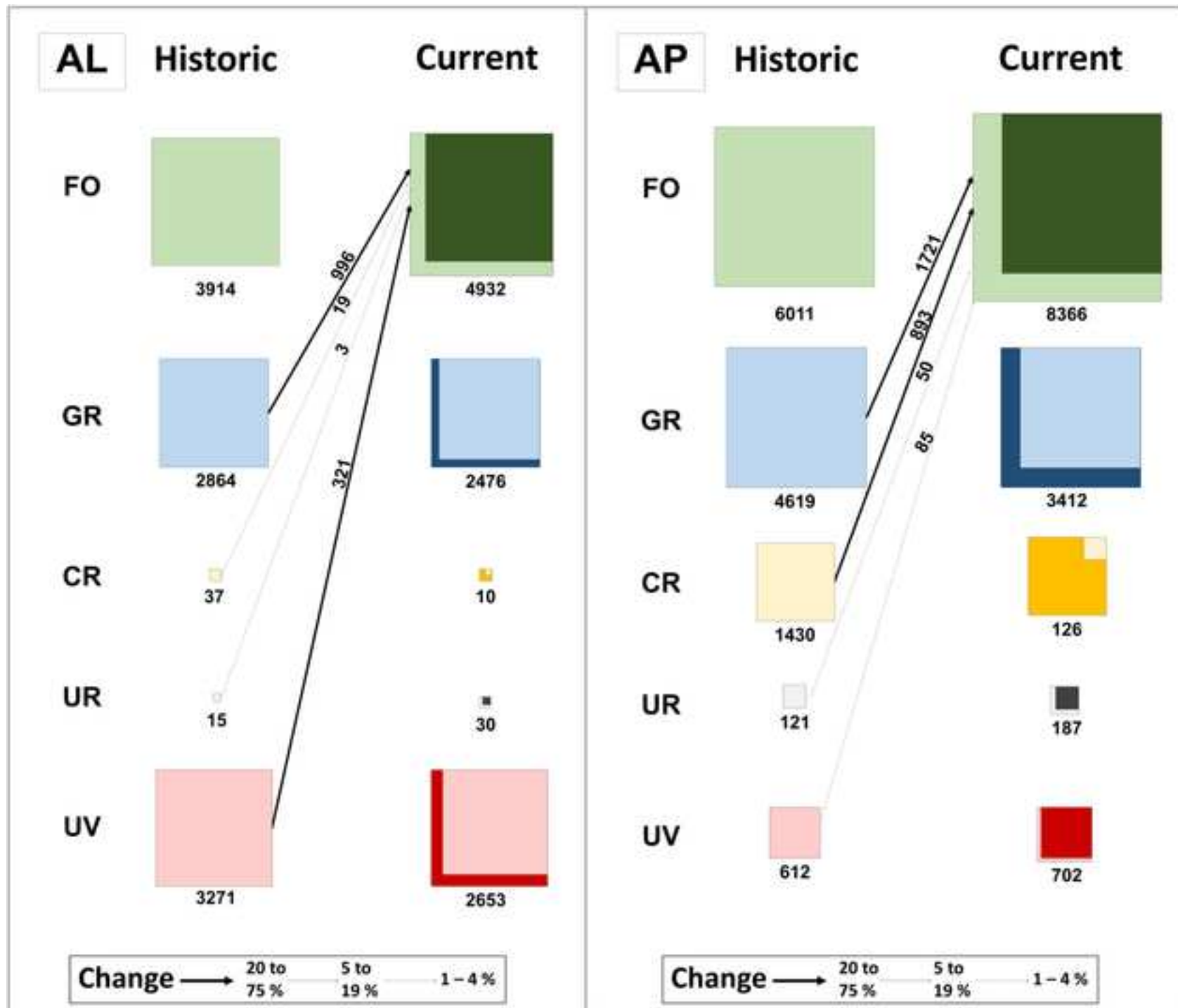
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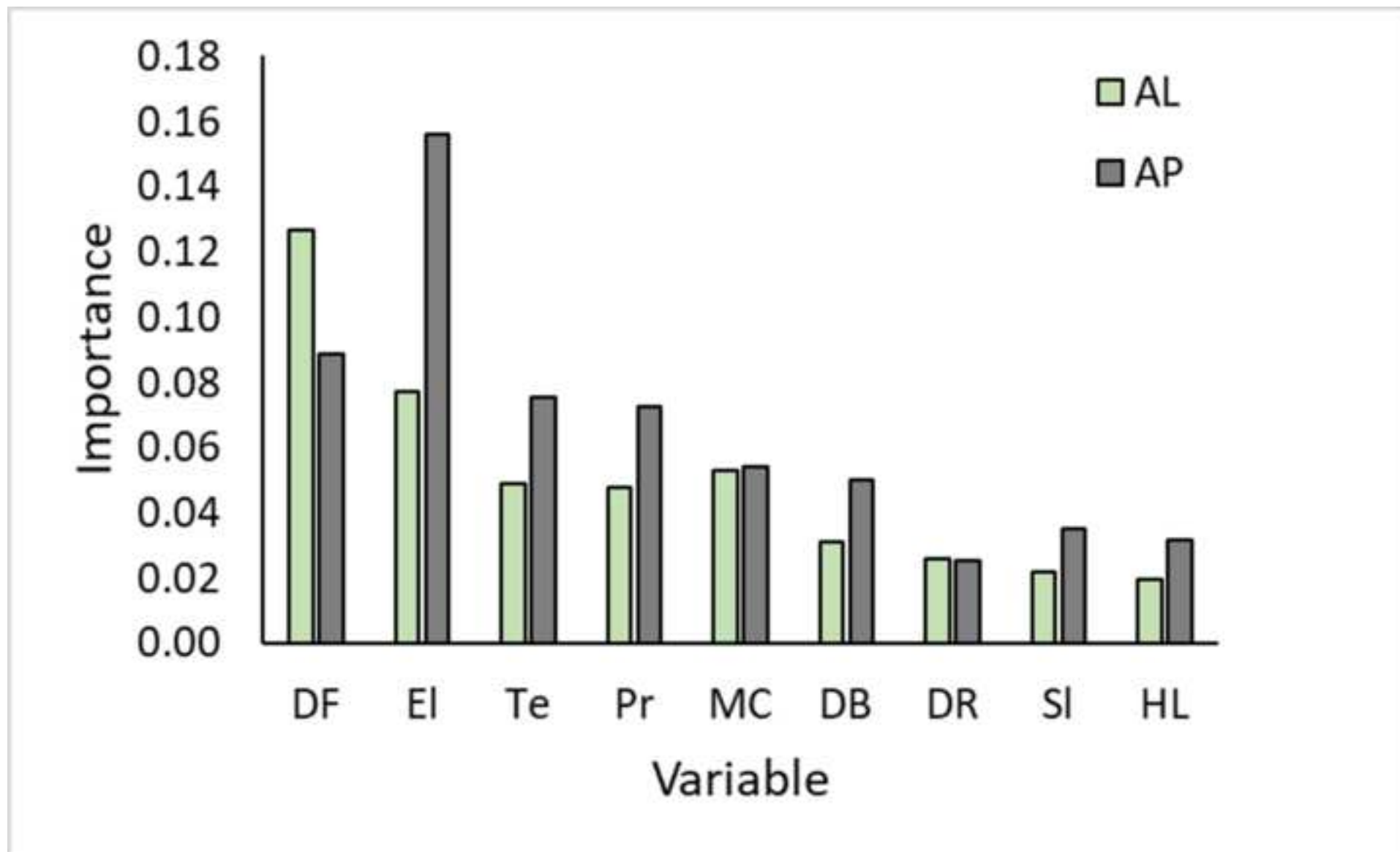
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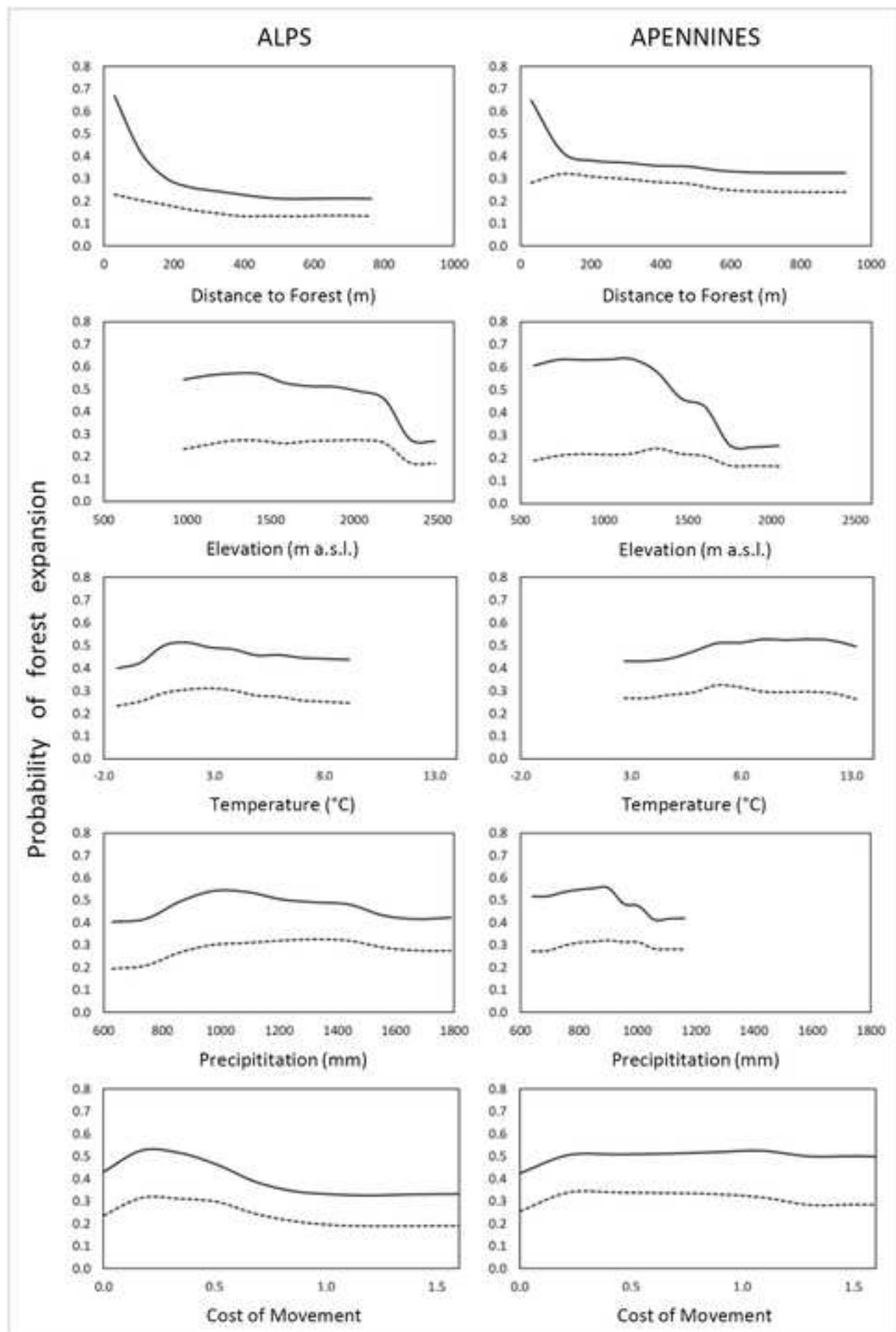
Figure 1











[Click here to view linked References](#)

Reply to reviewers related to the manuscript entitled “Contrasting land use legacy effects on forest landscape dynamics in the Italian Alps and the Apennines”. All the changes are highlighted in yellow within the Word document named “LAND-D-20-00035\_R1.docx”.

Reviewers	Comments	Replies
<i>GENERAL COMMENTS</i>		
R2	Overall, I felt that the analyses were sound and useful. However, clarity of certain portions of the methods section could be improved, and justification of some components (such as variable selection and selection of the focal landscapes) could be further detailed.	We better specified the rationale under the selection of landscapes and variables. See specific answers in the methods section.
R2	The paper is very well written, but would benefit from an additional review by the authors to catch several small grammatical errors (see specific comments below for some of these).	We fixed those grammatical errors following the specific comments.
R2	The two analyses that make up the core of this study (the CORINE land cover and air photos) felt a bit "detached" from one another and might be better integrated given that they convey similar ideas in similar study areas. In particular, I was surprised that the aerial imagery were discussed so much more than the CORINE land cover analyses. One suggestion below is to try to use the CORINE data to determine how representative the focal landscapes for the aerial imagery are of the broader Alp and Apennine ranges. Though there are probably other ideas that the authors may have for better integrating the two analyses.	To integrate CLC data and aerial imagery we added a table (S5) within the supplementary material to compare land cover proportions per year in the AL and AP regions. This table shows that at the landscape scale this data are not reliable because in some of our landscapes, due to CORINE misclassification, we observed a strong reduction of forest surface area, that is not the real situation. This is why we decided to discuss a lot more the aerial images derived data because we feel confident about the “quality” of our land cover maps, this is not the case of CORINE data. Another reason against the CORINE-aerial comparison is that this data analyze different periods of time (1990-2018 and 1954-2012, respectively).
R2	The effects of scale on the analyses and results could be further explored. One specific example is the selection of a 30 m spatial resolution in the Random Forest analysis.	The effect of scale was explored more thoroughly and methods/results sections are slightly modified. We added additional model results in the appendix section (Table S3).
R2	The mechanisms of forest expansion could be further elaborated in the discussion section to more strongly connect to fine-scale forest dynamics in these and similar systems.	We added some sentences in the discussion section to deepen the link between broad-scale forest expansion with species reproductive strategy.

R3	I have commented on some minor notes directly in the manuscript. Please note these. In addition, I have taken the liberty of including some literature citations specific to the Alps, which underline some points of discussion from the perspective of the Alps even more.	We report in this table all the comments by reviewer #3.
<i>SPECIFIC COMMENTS</i>		
R3	L 19: "dramatically" In some regions yes, in others much less.	That sentence was slightly modified.
R3	L 29: better "a-1"	Here and in the rest of the manuscript we used " yr <sup>-1</sup> ".
R2	L 46: "...and [associated] ecosystem services."	Modified accordingly.
R2	L 53: "...abandoned [cropland]..."	Modified accordingly.
R2	L 76: The wording "not directly comparable" here seems to undercut your point. Perhaps it could be restated? Or used to further justify the study by saying something like, "These estimates rely on a range of sources, and studies using consistent datasets to quantify changes in land cover across broad areas prior to widespread availability of satellite imagery are lacking."	We substituted that sentence with the suggested one.
R3	L 114: Where do these numbers come from? From my point of view these sums are far too high! Normally there is precipitation of 600-1600 (max. 2000) mm in the Central and Southern Alps.	We modified the sentence citing a recent paper by Isotta et al. (2013) highlighting the high variability that can be found in the Alpine region.
R2	L 114: As "drought" is typically used in a relative sense (relative to long-term conditions on a given site), perhaps this (and L 121) could be changed to "with a pronounced dry period during the summer" or something similar.	Right, we modified those two sentences accordingly.
R2	L 137-138: This section is related to a couple of my general comments above. I think that a justification for why these specific landscapes were selected would be helpful (was it based solely on data availability? Were they randomly selected from a pool of available images?), as would a description of how well they represent the broader conditions in each mountain range. In other words, are they representative samples or case studies? To determine this, perhaps a brief section in the appendix could be added that compares CORINE changes 1990-2018 within the (i.e., sample) of the study landscapes to the broader regional (i.e., population) results from CORINE presented in the first section of the results. I don't think this is necessary to add to the body of the paper (unless the authors choose to do so), but would be helpful in the appendix with a brief reference in the results to situate the study landscapes within the broader regions. I also think that it might be helpful to tie the two analyses together a bit more strongly.	<p>We added a sentence on landscapes selection: "These landscapes were selected and harmonized from previous projects and unpublished data on land-use/land-cover changes in AL and AP (e.g. Garbarino et al. 2013; Malandra et al. 2019". The landscape selection was necessarily random because of the different purposes of previous projects. We also believe they are representative of the studied mountain ranges because of the absence of a bias of our landscape scale data.</p> <p>Regarding the CORINE land cover data we added a table (S5) as a supplementary material reporting a comparison between the two different approaches (CORINE and</p>

		aerial images).
R2	L 151: Why were these specific parameters selected in segmentation? It might be an interesting addition to test multiple parameters in the segmentation and to show their influence on the outcome of the classification or RF analyses.	These specific parameters were selected after several tests performed on different aerial images during these and previous projects (e.g. Malandra et al. 2019, Garbarino et al. 2013, Garbarino et al. 2011).
R2	L 152-154: At first read, this description seemed to suggest that the authors manually classified all segments (following segmentation in eCognition) in each study landscape. However, I think that they actually performed a supervised classification of the objects based on an initial set of training polygons selected through photointerpretation. If this is the case, it could be more clearly stated here (including the general protocol and supervised classification method). If the analysts did in fact manually classify all objects, then additional information should be added to this section to describe the procedure in detail, including methods to reduce variability in interpretation among different analysts. If the classification was supervised and object-based, ensuring that accuracy assessment was performed at the object-level rather than the pixel-level would be important (see: Radoux, J., & Bogaert, P. (2017). Good Practices for Object-Based Accuracy Assessment. <i>Remote Sensing</i> , 9(7), 646. doi: 10.3390/rs9070646). Additional detail could be added to the description of the accuracy assessment for this classification.	Right, we performed a supervised classification of the objects based on an initial set of training polygons selected through photointerpretation and then we manually classified those polygons that were left unclassified by the supervised classification. We added a sentence clarifying these important methodological details, comprised the object-based accuracy assessment.
R2	L 158-159: Why were the maps smoothed with a majority filter? If I understood the previous section correctly, this is already an object-based image classification, so smoothing the classified map would just change a few pixels along object boundaries?	The 3x3 majority filter was used to avoid aberrant very small objects coming from the previous RS-GIS operations.
R2	L 161: Are the authors referring to Cohen's Kappa coefficient here with K? If so, it should be defined and explicitly stated as there are many K statistics in different fields for different purposes. Also, if this is Cohen's Kappa, it is typically presented as an index of -1 to 1 rather than as a percentage.	Right, we specified that we used the Cohen's Kappa coefficient and corrected percentage values to -1 to 1 values.
R2	L 166: I appreciate that the authors have already made these data publicly available. It was nice to be able to look at them while reviewing this manuscript.	That was the idea, thanks!
R2	L 167: For the Mann-Whitney test, I'm a little unclear about the unit of the analysis here. Was it the count of 30 m cells within each study landscape? Or was it the amount of change within each landscape? Specific descriptions of sample size and units of analysis would help improve clarity here.	Right, we added a sentence clarifying that we used a sample size of 8 landscapes to compare the contribution (in hectares) of each category (5 categories = 5 M-W tests) to the transition into forest.
R2	L 169: It is a little unclear to me if the authors looked	Right, that part needed more

	<p>only at cells that were unforested in the c. 1960 imagery for this analysis. So, the response was, for every 30 m cell (that was not forest in the 1960 period), a binary condition of 1) forest gain or 2) no transition or transition to another cover type? What about cells that were forest initially? This could be further clarified.</p>	<p>detailed explanations. We in fact considered only unforested pixels (30m size) and filtered out from the dataset those pixels that were forested in the past. Among the former unforested pixels we gave 1 to forest gain and 0 to unchanged or other transitions.</p>
R2	<p>L 173: Wouldn't this more appropriately be described as "1 m cells were aggregated to a 30 m resolution using the majority class within each 30 m pixel" or something similar? Nearest neighbor is more of an interpolation tool than an aggregation tool, and would imply that each 30 m cell in the aggregated map took the class label of the closest 1 m cell in the original map.</p>	<p>Right, we changed this part and the following analyses by using a majority resampling technique instead of using the NN.</p>
R2	<p>L 175-177: Given the target journal (scale being one of the key concepts in Landscape Ecology), I was a little surprised that this point was not discussed in more detail. I think this is particularly important because the RMSE of co-registration error (i.e., 23 m) means that some 30 m cells may actually be compared to an adjacent cell during the change detection. If results of the Random Forest analyses were qualitatively similar for the 30 and 60 m resolution (similar variable importance and trends in partial dependence) then the authors might present this (briefly) in the text, or as a separate figure in the appendix. If the variable importance and partial dependence plots were substantially different, then I think the scale-dependence of these results should be discussed quite a bit more than it is currently. One point of particular importance is that with this offset and a 30 m cell size, some cells that "transitioned" to forest along the previous forest edge could actually have been stable through time, but only appeared as change due to the offset between the two images. However, if the results are similar between 30 and 60 m then this may not be an issue. Either way, discussing this in further detail would be useful.</p>	<p>We explained more in detail the choice of the 30 m resolution and we added results regarding the RF model at 60 m resolution in the supplementary materials (Table S3). Specifically, our results showed that RF models were scarcely dependent on the spatial scale of the data and that the influence of co-registration errors on model predictions at 30 m was limited given the similarity with results obtained using data at 60 m resolution.</p>
R3	<p>L 182: For landscape codes see Table 1</p>	<p>We added the suggested sentence to that figure caption</p>
R2	<p>L 189-192: This section could benefit from a table, either in an appendix or in the main text, that lists all of the specific predictor variables, why they were included, and the authors' ideas of what they represent related to forests in these regions.</p>	<p>We agree and added a table (S4) in the supplementary material.</p>
R2	<p>L 199-201: I really like this approach of spatially stratified cross-validation in tuning hyperparameters. Any particular reason that eight clusters were selected? Given the nature of the data, I think that it might also make sense to use this spatially-stratified</p>	<p>The reason why we chose 8 partitions is that it corresponds to the number of landscapes in each mountain range, thus it should guarantee an adequate spatial</p>

	<p>method when calculating the predictive ability of the RF models themselves rather than using the default out-of-bag error. This would help to better assess the ability of these models to generalize to new areas.</p>	<p>partitioning. We ascertained this by plotting the spatial partitions of points created through repeated clustering of points coordinates based on k-means. Moreover, this number falls within the optimal number of partitions for cross-validation, ranging from 5 to 10. Now we assessed the predictive performances of the models using the Brier score and the AUC evaluation measures. We used a nested spatial cross-validation strategy in order to perform both repeated cross-validation and hyper-parameters tuning as described in the manuscript.</p>
R2	<p>L 211: For clarity, subsection titles could be modified to refer to specific data being used. For example, this subsection could be titled "Regional land cover changes - CORINE" and the following subsection could be "Landscape transitions - aerial imagery." Or the dataset could be referred to explicitly in the first sentence of text within each subsection. Here, something like: "Based on our analysis of CORINE land cover data from 1990-2018 in AL and AP, we found..." As it reads now, I had to glance back to the methods to remind myself what was being compared in each section.</p>	<p>We like the suggestion and modified the subsection titles.</p>
R3	<p>L 215: Realistic in such short time?</p>	<p>We believe that it is realistic at regional scale</p>
R2	<p>L 217: Nice. I think that the addition of this simple analysis with CORINE makes this more broadly interesting.</p>	<p>We agree with this.</p>
R3	<p>L 219: In my opinion, the change in area could also be expressed as a percentage of the total mountain area, allowing a direct comparison between mountain regions and a relativisation of the individual land cover changes.</p>	<p>We agree and modified the table accordingly.</p>
R3	<p>Table 2: I am surprised at the high proportion of this class. It is possible that Alpine grasslands was also included in the class. On unvegetated land a forest occurrence in such a short time is more than unrealistic. Normally there is no suitable soil. Please check.</p>	<p>With the new version of table 2 it is probably clearer that the high amount of UV category in the Alps (10%) is not a change, but the proportion of this category on the total surface of the alpine region that is rich of rocks, glaciers, gravel, etc... The % absolute change for this category is around -1, not so much.</p>
R3	<p>L 226: crops (CR)</p>	<p>Modified accordingly.</p>
R2	<p>Figure 2: I really like this figure but have a couple of suggestions. First, a different color palette might</p>	<p>We modified the colors in this figure to increase the contrast</p>

	<p>make things more visually appealing as the colors used here come off as a little "harsh" to the eye, particularly the light green and light blue. For example, "Set2" and "Dark2" in RColorBrewer might be nice choices for light and dark discrete palettes, or the "paired" palette that has paired light and dark colors. Second, I am a little bit unclear on the descriptions and use of "transitioning" vs "persistent" colors in this figure. It is hard for me to tell for sure, but in some cases (e.g., UV class in AL; GR class in AL and AP) the light-colored box actually represents persistence? Whereas in the FO class, the darker boxes appear to be persistence. Also, in at least one instance (e.g., CR to FO in AP), the number on the arrow is greater than the initial cover. Perhaps this is a typo in the label of the area of the CR class in AP historic?</p>	<p>between persistent and transitioning surfaces.</p> <p>We also improved the figure caption in order to make it clearer the difference between "transitioning" vs "persistent" land cover categories.</p> <p>We also fixed the typo in the label of CR category in AP.</p>
R2	<p>L 248: The numbers in parentheses here and later should be defined. Perhaps "importance =" with first use and "imp. =" after that?</p>	<p>We modified it by using the symbol "IR" meaning importance rate.</p>
R2	<p>L 249-251: Presumably, the climatic variables used in this analysis are strongly related to elevation and terrain. In the methods section, the authors might add a stronger justification for why they were all included instead of just climate or just topography. For example, climate could vary latitudinally (particularly in AP) or with distance to coastline (in AL) in ways that make these variables represent slightly different things than elevational trends in temp and precip. Alternatively, the authors could use a metric like climatic water deficit or actual evapotranspiration (e.g., Lutz et al. 2010; Journal of Biogeography) to combine the effects of temperature, precipitation, and heat load into a single variable at a higher resolution. At 1 km (which is a fairly high-resolution climate surface), the climatic predictors are still somewhat coarse compared to the 30 m unit of analysis, and there may only be a few unique climate cells within some of the smaller landscapes.</p> <p>This coarse spatial resolution seems like it has the potential to influence results of variable importance and OOB error (though using spatially-stratified cross-validation rather than OOB error might help to account for this component). I totally understand if the authors choose to use climate variables in the final analyses, but if they do, some discussion of the limitations of data resolution and its potential influence on the results would be valuable.</p>	<p>We understand the criticism raised by the reviewer, but the climatic dataset that was used (CHELSA) is less strongly influenced by topographic gradients compared to other climatic datasets (e.g. WorldClim).</p> <p>Anyway we added a sentence at the bottom of the discussion section reporting the limits of this approach linked to the spatial resolution mismatch between topographic-vegetation variables and climatic ones.</p>
R2	<p>Figure 5: Based on Fig. 4, it seems like the authors picked variables 1-3 and 5 for plotting. Why only these? Excluding the fourth ranked variable seems a little bit like cherry-picking what they thought were</p>	<p>Figure 4 and figure 5 were replaced by new versions following the new analyses made with resampled landscapes. In addition, we added</p>

	<p>the more the interesting results. I realize that there may not be enough space to show all of the partial plots, but including all of them in an appendix might be useful, and then specifically saying "We plotted the top 5 variables from each region and the remainder are in the appendix" or something along those lines. Also, for plotting, shouldn't the SD lines of partial dependence be included above and below the predicted effect as a sort of confidence interval? Rather than just below it?</p>	<p>the variable precipitation, in this way we plot the 5 most important predictors for both mountain ranges. We plotted SD lines only below the averaged predicted effect because they were presented in this way by the authors of the Individual Conditional Expectation plots (see Goldstein et al. 2015)</p>
R2	<p>L 281-282: The Norman et al. (2005) citation is a little bit dated for this kind of research in the western U.S. More recent citations showing afforestation in California -Lydersen, J. M., &amp; Collins, B. M. (2018). Change in Vegetation Patterns Over a Large Forested Landscape Based on Historical and Contemporary Aerial Photography. <i>Ecosystems</i>, 21(7), 1348-1363. doi: 10.1007/s10021-018-0225-5 and Colorado - Rodman et al. (2019; already cited in methods section)</p>	<p>We modified that citation accordingly.</p>
R3	<p>L 286-287: Some examples:  Tasser, E., Teutsch, A., Noggler, W. &amp; Tappeiner U. (2007) Land-use changes and natural reforestation in the Eastern Central Alps. <i>Agriculture, Ecosystems and Environment</i> 118: 115–129.  Fontana, V., Radtke, A., Walde, J., Tasser, E., Wilhelm, T., Zerbe, S., Tappeiner, U. (2014) What plant traits tell us: consequences of land-use change of a traditional agro-forest system on biodiversity and ecosystem service provision. <i>Agriculture, Ecosystems and Environment</i> 186, 44-53.  Seidl, R., Albrich, K., Erb, K.-H., Formayer, H., Leidinger, D., Leitinger, G., Tappeiner, U., Tasser, E., Rammer, W. (2019) What drives the future supply of regulating ecosystem services in a mountain forest landscape? <i>Forest Ecology and Management</i> 445, 37-47.  Wallentin G., Tappeiner U., Strobl J., Tasser E. (2008) Understanding alpine tree line dynamics: an individual based model. <i>Ecological Modelling</i> 218/3-4: 235-246.  Tasser, E., Leitinger, G, Tappeiner, U. (2017) Climate Change versus Land-Use Change - which affects the landscape more? <i>Land Use Policy</i> 60: 60–72.</p>	<p>These papers are all very interesting, but we decided to cite the first two because they compare different landscapes in alpine regions characterized by post-abandonment forest expansion.</p>
R3	<p>L 293: Similar rates are also documented for the Alpine regions Carnia (0.7% a-1), Tyrol (0.35% a-1) and South Tyrol (0.1% a-1) in the period 1955 to 2000 (Tasser et al. 2007).</p>	<p>We added the whole sentence that gives an international breath to our paper.</p>
R3	<p>L 304-305: Some information in Zimmermann, P.D., Tasser, E., Leitinger, G., Tappeiner, U. (2010) Effects of land-use and land-cover pattern on landscape-scale biodiversity in the European Alps. <i>Agriculture,</i></p>	<p>Right, we added that citation too.</p>

	Ecosystem and Environment 139: 13–22.	
R2	L 306: As written, this kind of undersells the authors' analyses with CORINE. If I understand the issues with CORINE correctly (based on a quick look at the referenced paper) it seems like the primary issue is differences in mapping accuracy among different nations. Given that the study area is within a single country, this may not be an issue? So, perhaps this citation and portion of this sentence could be removed. Classification accuracy may be an issue, but this (and inaccuracy in classification of the air photos) could perhaps be briefly discussed in a limitations section instead. Similarly, classification accuracy of the CORINE datasets is not broadly quantified, but this could be completed pretty easily for the authors' study area (at least for a recent time period and the five aggregated classes) and it seems as if this would be a valuable contribution to the literature.	We removed part of that sentence accordingly. Anyway, the lack of speculative discussion on the CORINE analysis within our manuscript is due to the fact that even on a large study area such as the whole Italian Alps and the Apennines we found a sinusoidal behavior of forest surface trend from 1990 to subsequent study years.
R3	L 312: Hard to do in such a short time. I think there are classification problems.	The transition from unvegetated areas to forest is not so hard to believe. This is due to the fact that within this category we grouped rocks, gravel, sands, bare soil and sparse grasslands or sparse vegetation. The latter is a subcategory, mostly located at high elevation (between 2000 and 3000 m a.s.l.), composed by a mosaic of grasses and stones/sands.. Here the competition of encroaching trees with grasses and shrubs is less limiting. We added a sentence to methods section to explain the variability of this land cover category.
R2	L 316: If there is relevant literature, perhaps the authors could briefly discuss the methods of afforestation. Is it entirely from seed? Are there any places in which resprouting species had belowground tissue and are quickly growing back? This might be particularly important in rangeland/pastoral areas that were not intensive cropland - where grazing could allow resprouting species to persist but only at very low densities. A bit more about the ecology of these forest systems and mechanisms of expansion and infilling would be interesting in this paragraph or the next.	We added a couple of sentences and citations describing the main reproductive strategies of European beech and Mediterranean mountain pines.
R3	L 319-321: For the Alps: Zimmermann, P.D., Tasser, E., Leitinger, G., Tappeiner, U. (2010) Effects of land-use and land-cover pattern on landscape-scale biodiversity in the European Alps. Agriculture, Ecosystem and Environment 139: 13–22.	We added that citation for the Alps.

R3	L 322-328: See: Tasser, E., Teutsch, A., Noggler, W. & Tappeiner U. (2007) Land-use changes and natural reforestation in the Eastern Central Alps. Agriculture, Ecosystems and Environment 118: 115–129. Wallentin G., Tappeiner U., Strobl J., Tasser E. (2008) Understanding alpine tree line dynamics: an individual based model. Ecological Modelling 218/3-4: 235-246.	We added that citation for the Alps.
R3	L 336-338: See: Tasser, E., Leitinger, G, Tappeiner, U. (2017) Climate Change versus Land-Use Change - which affects the landscape more? Land Use Policy 60: 60–72.	We added that citation for the Alps.
R2	L 340: Shouldn't "legacy" be plural in this case? As in "disturbance legacies" or "biological legacies"?	Right, we modified accordingly.
R2	L 349-351: The effect of aspect (or heat load) is contingent upon elevation, correct? South-facing slopes at low elevations are fundamentally different than those at high elevations. It seems like they should be discussed together here to bring out some of that nuance. This same comment applies to the abstract. Climate is probably not universally more suitable for forests at low elevations?	We modified that sentence, accordingly.
R2	L 350: Perhaps "greater" rather than "larger"	We modified that sentence, accordingly.
R2	L 358-360: This sentence and the final one in the paragraph could use citations to support them.	We added those citations.
R2	L 368: The negative effects of afforestation in Italy could be listed here explicitly to help folks that are unfamiliar with management concerns in these regions. It is discussed in the intro but could be brought up again here.	We added a sentence to expand a bit more these concepts.
R2	L 378: This should be "legacies of land use" or "land use legacies", correct?	We used "legacies of land use".
R2	L 379: Perhaps use: "...forest edges in combination with environmental factors such as..."	We modified that sentence, accordingly.
R3	L 378-385: This part contains only a summary and repetitions of the most important results. From my point of view this part should be deleted.	We decided to maintain this part because is a sort of concluding paragraph where we also highlight the limits of our research approach.
R2	L 387-388: I finished the article expecting more of a connection to the "big picture context" in the last paragraph. The authors do a nice job of this in the intro and in the start of the discussion, but this last paragraph could be adjusted slightly by connecting to some broader theoretical concepts or global issues. A couple of potential suggestions: 1) global patterns of afforestation vs deforestation and the carbon balance, or 2) linking recent change again with past patterns of forest cover and paleoecological literature (as is done effectively throughout the intro and reviewed in Vacchiano et al. 2017, Forest Ecology and	We added few sentences at the end of the discussion section, following the suggestion #2 of the reviewer #2.

	Management). Idea #2 could be situated in an interesting way to bring up the tricky question of "what is natural", "what is the desired condition", and are these convergent or achievable goals in a landscape heavily influenced by human impacts over many millenia.	
R3	Table S1: or grassland? (instead of "Sparsely vegetated areas")	No, this is the official legend of CORINE land cover maps.

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The order of authors of our manuscript was slightly modified to better reflect the level of contribution of authors. In particular, the “position” of Prof. Carlo Urbinati changed from 6th to 3rd, because while making the revisions suggested by the reviewers, the contributions by CU became greater, increasing his level of contribution to the overall paper.

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4 <sup>th</sup> author	Francesco	Malandra
5 <sup>th</sup> author	Renzo	Motta
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Matteo Garbarino conceived the experiment and all authors contributed to the study design. Material preparation, data collection and analysis were performed by Matteo Garbarino, Donato Morresi, Emanuele Sibona, Francesco Malandra, Alessandro Vitali and Carlo Urbinati. The first draft of the manuscript was written by Matteo Garbarino and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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