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Planning coastal Mediterranean stone pine (*Pinus pinea* L.) reforestations as a green infrastructure: combining GIS techniques and statistical analysis to identify management options

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Abstract Mediterranean stone pine reforestations are common characteristics of the Italian Tyrrhenian coast, which mostly maintain uniform and monolayered stand structures. However, improving structural diversity is an effective climate change adaptation strategy in forest management. The aim of this study was to implement a methodology which allows distinct reforested areas such as a single green infrastructure to be managed according to the surrounding land use and the characteristics of the forest stands. 240 hectares of Mediterranean stone pine forests located along a 16 km strip of the Lazio coast (Central Italy) were mapped. Twelve attributes describing the pine stands and showing possible constraints for future management decisions were associated to each forest patch. A hierarchical cluster analysis was performed to group the pinewood patches according to their similarity level and five different groups were identified. For each group, different silvicultural methods were proposed to guide the compositional and structural evolution of the stands, in order to make them suitable for providing services required locally and increasing overall diversity at landscape scale. The results of the study highlight how coastal land uses can offer effective inputs to differentiate the management of forest systems and therefore achieve greater variety and resilience in the landscape over time. This approach is particularly useful in the case of very homogeneous stands such as the stone pine reforestations under study.

Keywords: *Pinus pinea* L., coastal transition zone, coastal reforestation, forest landscape planning, green infrastructure, buffer analysis.

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Introduction

The land-sea interface or Coastal Transition Zone (CTZ) (*sensu* Schaefer 1972 in Talley et al. 2003) is a landscape that has undergone significant land use changes over the centuries due to strong anthropogenic pressure. Coastlines are the most densely populated areas of the EU states: 35% of the inhabitants live within 5 km from the shoreline (EUROSTAT 2011) and the EEA (2013) reported that EU littoral Countries experienced a rise of sealed surfaces ranging from 2 to 13% within the first 10 km from the coastline over a 4-year period. The high demand for coastal land resources for tourism, recreation and other economic interests has caused severe impacts which have jeopardized the extent and functionality of plant communities (Curr et al. 2000, Davenport & Davenport 2006, Ciccarelli 2014, Hernández-Cordero et al. 2017, Muñoz-Reinoso 2021). Conversely, coastal ecosystems are deemed to be important in different bioregions due to environmental, economic and social value of the services provided (Martínez et al. 2007, Luisetti et al. 2011, Barbier et al. 2011, Jusoff 2013, Liquete et al. 2013, Ovando et al. 2016, Tomao et al. 2016, 2018). For this reason, there has recently been great interest in monitoring the dynamics of coastal landscapes and in the restoration and proper management of coastal ecosystems (Schlacher et al. 2008, McLachlan et al. 2013, Lazarus et al. 2016).

The sandy coasts of the northern Mediterranean Sea have often been reforested for productive and protective purposes (Van der Meulen & Salman 1996, Butler et al. 2000, Del Perugia et al. 2017, Mechergui et al. 2021). *Pinus pinea* L. (Mediterranean stone pine or umbrella pine) has frequently been planted due to its adaptability to warm climates, edible fruit production, landscape value and because it is deemed to be a native or naturalized species in western Mediterranean countries (Martínez & Montero 2004).

In Italy stone pine forests cover an area of over 46000 ha which are mainly located along the western coast of the peninsula (INFC 2005). However, today climate change, growing anthropogenic pressure and the expansion of the Western conifer seed bug (*Leptoglossus occidentalis* Heideman) are damaging these stands (Luchi et al. 2012, Sancho Dos Santos & Wilton de Vasconcelos 2012, Mutke et al. 2017, Farinha et al. 2018, Freire et al. 2019, Calama et al. 2020), thus jeopardizing wood and fruit production. Conversely, these reforestations provide multiple ecosystem services: protection of agricultural crops from sea wind, tourism development (Tomao et al. 2016, 2018) and they curb urban sprawl (Gasparella et al. 2017, Grotti et al. 2019). Moreover, forest stands have often proved to maintain varied coastal vegetation, although in the past they have been criticized due to the negative effect they can have on biodiversity (Van der Meulen & Salman 1996, Marchante et al. 2003, Bonari et al. 2017).

For these reasons, forest management methods in coastal pinewoods should differ to those used in more productive areas. To date, studies on *Pinus pinea* stands have mainly focused on pine nut production from natural forests and plantations (Piqué et al. 2013, Piqué-Nicolau et al. 2013, Calama et al. 2016, Awan & Pettenella 2017), genetic improvement, selection, breeding and nut quality (Nergiz & Dönmez 2004, Mutke et al. 2013, Örnek et al. 2015, Mutke et al. 2019, Moscetti et al. 2021). Contrastingly, few studies have analysed the management of stone pine forests when non-marketable products are more important than timber and fruit yield even if climate change is known to negatively impact the growth, health and vitality of this conifer thus threatening the continuity of the numerous benefits these pinewoods provide to the local communities (Mazza et al. 2011, Mazza & Manetti 2013, Natalini 2016, Loewe

Munoz et al. 2015, Pardos et al. 2015, Calama et al. 2021, Merchergui et al. 2021). It is therefore essential to define specific short- and long-term management goals and criteria as well as silvicultural approaches in order to safeguard these coastal forest systems and reduce the risk of damage by fire (Dale et al. 2001, Corona et al. 2015, Mancini et al. 2017, 2018), human pressure (Gasparella et al. 2017) and poor management.

Bearing these considerations in mind, a strip of *P. pinea* reforestations established during the last century on a long stretch of the Tyrrhenian coastline was examined. The aim of this study was to identify appropriate silvicultural intervention criteria to apply to the pine stands along the various stretches of coast in order to obtain greater diversity in the overall forest structure.

The fundamental idea was to consider the reforestation complex as a green infrastructure offering numerous benefits to the environment, agricultural practices and tourist activities.

The type of functions required may vary according to the characteristics of the land use mosaic around the individual reforestation patch. In other words, the green infrastructure concept has been used as a unitary planning reference within which silvicultural decisions can be made in order to enhance the future structure of the individual pine stands in various ways. The aim is to plan diversity at landscape scale rather than to adopt a uniform management system across the board. Landscape scale planning is the most effective tool for managing forest multifunctionality as it enables us to link the functions to the context (Baskent & Yolasigmaz 1999, Setten 2012).
A methodology combining GIS techniques and statistical analysis is proposed with the aim of discriminating groups of reforestation patches according to the characteristics of the single pine patch and the surrounding landscape, which would enable us to define the most suitable management options for each group of patches and consequently differentiate the structure of future pine forest stands along the coastal landscape as much as possible.

Materials and Methods

Study area

The study site is located in central Italy in the province of Viterbo in the north of the Lazio region (42° 16’ N – 11° 36’ E) (Figure 1), where a narrow discontinuous strip of stone pine reforestations stretches along almost 50% of the Tyrrhenian sandy coast (16 on a total length of 36 km). The pinewoods were mainly established in the middle of the 20th century by the State Forest Service, the Reclamation Consortium of the Etruscan Maremma and private landowners. The main purpose of the reforestation work was to restore forest vegetation, stabilize wandering dunes and protect the crops behind from sea winds (Agrimi et al. 2002, Del Perugia et al. 2017). In order to ensure the success of these reforestations, stone pines were very densely sown along 8 m-wide strips of tilled soil parallel to the coast, alternated with unploughed strips of residual Mediterranean maquis (2 to 4 m wide) which protected the pine seedlings from the drying effect of sea winds. The most recent pine forest stands were planted. The broadleaved vegetation can still be seen as stunted understory in some stands under the pine cover. The edge of the reforested area near the sea was at least 35 m from the shoreline, however sea erosion gradually moved the boundary towards the pinewood.

A coastal dune vegetation belt lies between the pine forests and the shoreline in some stretches of the coast. Two Natura 2000 sites (codes: IT6010027 and IT6010027) were created in order to protect two littoral sections where dune vegetation is very well preserved. The sites include some pine reforestations classified as priority habitat 2270* (wooded dunes with forests of *Pinus pinea* and/or *Pinus pinaster*).

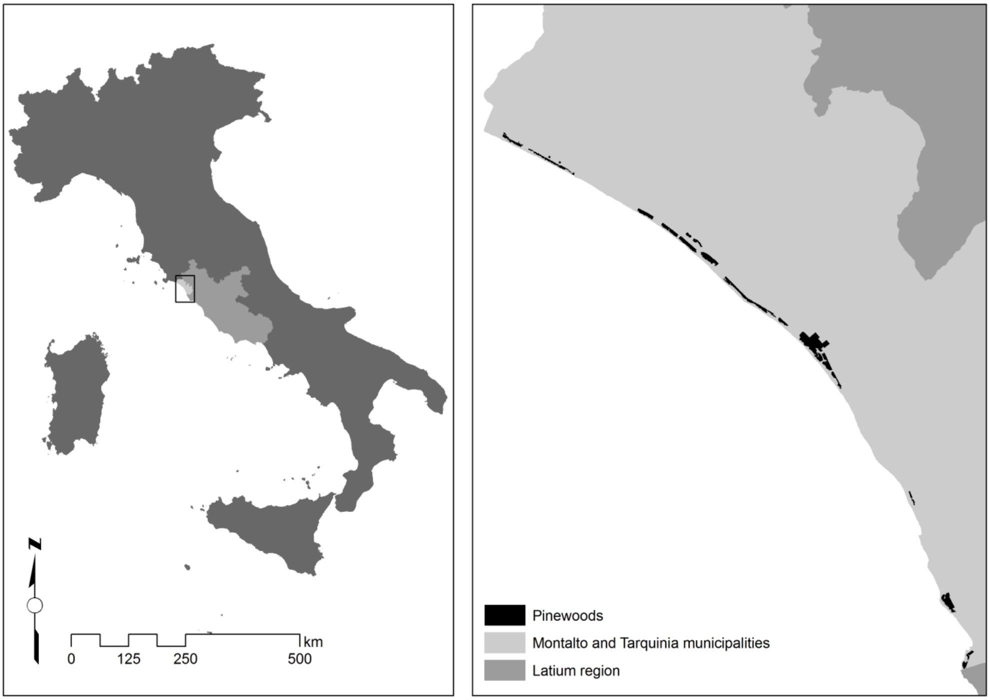

Figure 1 Geographical position of *Pinus pinea* reforestations along the Northern coast of the Lazio region.

Pinewood mapping

In first step of the proposed methodology (see Figure 2), the patches of stone pine reforestation were mapped through photointerpretation of high-resolution airborne imagery (geometric resolution < 50 cm) for the year 2014 and subsequently checked to obtain an error-free photo-interpretation using Google Map images and tools (GEarthView and StreetView plugins of QGis).

The following parameters were considered for the visual interpretation: (i) area > 500 m^2 without pine canopy interruption caused by pathways, roads, large clearings, buildings, or residual stretches of natural forest vegetation, etc.; (ii) tree canopy cover ≥ 10% (FAO 2001); (iii) width > 20 m (FAO 2001); (iv) minimum height of trees *in situ* ≥ 5 m (FAO 2001). Although the FAO established a 5000 m^2 threshold as the minimum surface area of a forest, a lower threshold was used in order to better describe fragmented landscapes. A 500 m^2 threshold was

Table 1 List of the variables associated to each pinewood polygon.

Variable	Unit of measure	Source
Stand age	N° of years	Field surveys
Pinewood forest type	Categorical (1: Belt pinewoods, 2: Mixed with *Pinus halepensis*, 3: Prostrated pinewood, 4: Pure even-aged)	Lazio forest type map (Chirici et al. 2014)
Included in a Natura 2000 Sites of Community Importance (SCI)	Categorical (0: No; 1: Yes)	Italian official databases of Natura 2000 network
Use of stand as campsite	Dummy (0: no; 1: yes)	Field surveys
Ownership type	Categorical (1: Public; 2: Private; 3: Collective)	Cadastral surveys
Pine patch size	ha	GIS analysis
Perimeter	meter	GIS analysis
Area/perimeter ratio (A/P)	-	GIS analysis
Land use rank of naturalness in buffer areas (see also Table 2)		
100 m buffer towards the inland	Categorical (1 to 10)	GIS analysis
100 m buffer seawards	Categorical (1 to 10)	GIS analysis
500 m buffer towards the inland	Categorical (1 to 10)	GIS analysis
500 m buffer seawards	Categorical (1 to 10)	GIS analysis

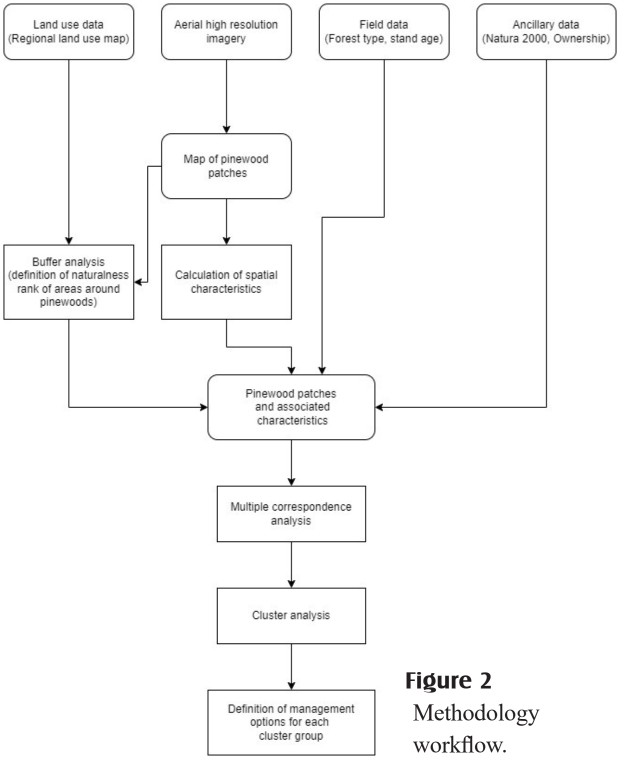

Figure 2 Methodology workflow.

Table 2 Naturalness rank of the land uses in the buffer areas according to prevalent and secondary (in brackets) land uses. See the text for more details.

Naturalness level	Land use	Rank of naturalness
	Urban areas	1
	Urban areas (agricultural areas)	2
	Urban areas (campsite)	
Low	Urban areas (sea)	
	Urban areas (beaches and sand dunes)	
	Campsite	3
	Campsite (agricultural areas)	
	Agricultural areas (urban areas)	4
	Agricultural areas (campsite)	
	Agricultural areas	5
Medium	Agricultural (pine reforestation)	6
	Agricultural areas (native forest)	
	Agricultural (sea)	
	Agricultural areas (beaches and sand dunes)	
	Pine reforestation (urban areas)	7
	Pine reforestation (campsite)	
	Pine reforestation (agricultural areas)	
	Pine reforestation	8
	Pine reforestation (native forest)	9
	Pine reforestation (sea)	
High	Pine reforestation (beach and sand dunes)	
	Native forest	10
	Native forest (agricultural areas)	
	Native forest (sea)	
	Native forest (beach and sand dunes)	
	Beach and sand dunes	
	Sea	

used to identify all pinewood patches within the study area, including small and fragmented patches. A total of 68 polygons were detected which covered an area of approximately 240 ha (median value of 1.9 ha per polygon).

Variables associated to pinewoods

Pine stand attributes and possible constraints for future management options were associated to each polygon (table 1) according to field and ancillary data. Four variables synthetically describing land use quality around each pine patch were then considered in order to link future management to the geographical and socio-economic contexts in which the pinewoods are located (Table 1). Land use around each polygon was classified within two buffer areas (100 m- and 500 m-wide) according to the Lazio region land use map (available at https://geoportale.regione.lazio.it/geoportale/) (Gasparella et al. 2017). Two sides of the buffer areas were considered: towards the sea and towards the inland. Based on the prevalent (i.e. that covering most of the buffer area) and secondary land uses (Table 2), the buffers were assigned a rank of increasing naturalness ranging from one to ten, corresponding to a decreasing level of anthropogenic pressure. Due to the lack of operational references in literature, the rank scheme was defined by the authors, researchers working in the field of urban planning and/or landscape ecology and professional foresters.

Results

Descriptive statistics

The pinewoods considered in this study share the same stand structure: 95% are currently classified as pure even-aged pinewoods. Only 9% of the pine forests have campsites, over 29% are privately owned while 44% and 27% are publicly and collectively owned, respectively. Almost half (53%) of the reforestations are classified as priority habitats (see § 2.1) and flanked by well-preserved dune vegetation (Carboni et al. 2009). The biodiversity of the coastline in these stretches of the shoreline is very rich.

Towards the hinterland, "Agricultural areas" is the main land use (classes 4, 5 and 6) and approximately 50% of the territory is characterized by land uses with a high degree of anthropization (classes 1 to 5). In the 100 m-buffer areas, there is less human impact (Table 3).

Table 3 Percentage of pine reforestation patches in whose buffer areas the land use has low level of naturalness (1 to 6 classes).

Buffer area category	1 to 5	4 to 6	Most represented classes
100 m towards the inland	47.0	36.7	5
500 m towards the inland	66.1	60.2	4-5
100 m seawards	14.7	5.8	9
500 m seawards	4.4	1.5	10

On the other side the landscape is dominated by beaches and the sea with a few types of land use in classes one to five due to the construction of tourism infrastructures. Many pine forest patches are joined to or in proximity to others.

The size of the pinewood patches ranges from 0.05 ha to more than 30 ha (median value of 1.9 ha), highlighting the fact that the area is composed of a patchwork mosaic of small reforested surfaces interspersed with strips of residual native vegetation and tourist infrastructures rather than a continuous system of long strips of pine forests.

Cluster analysis

The results of the cluster analysis are shown in Figure 3. Five different groups were identified. Group number 1 is characterized by moderate internal variability. In fact, the dissimilarity measure among the pinewood patches in this cluster reaches values just over 10. The smallest cluster is cluster 2 with only five pinewood units, while group 5 has the largest number of units (28). Cluster 5 is also well separated having a dissimilarity measure from the other four clusters higher than 30.

The characteristics of the pinewoods belonging to the five different clusters were determined using the conditioned frequency analysis (table 4 and table 5). The χ^2 non-parametric test showed that all variables are interdependent with the cluster groups *($p<0.01$)*.

Cluster 1 is composed of mature and adult pinewoods that are often used as campsites, which lie within a highly anthropized landscape both towards the sea and the inland, where the two main seaside resorts along the Viterbo coastline are located. These regularly-shaped pinewood patches are composed of medium-large trees and are subjected to intense recreational use, therefore the entire surface area must be easily accessible. The stand structure, which is monolayered with continuous cover and sparse or no undergrowth of sclerophyllous species, is suitable for its current use. The management will be responsible for the health and stability of the individual trees in order to maintain a continuous canopy cover and minimise the risks to user safety. Trees at risk of failure that stand directly on the camping facilities should be promptly cut down. Therefore, it is advisable to rotate the camping areas to allow the new trees time to establish themselves and to recreate even shade. A patch belonging to this cluster is located inside one of the Natura 2000 sites. However, it is partially used as a campsite as it is part of the bordering tourist resort.

Cluster 2 is a small group of medium-sized and regularly-shaped mature pinewoods surrounded by small areas of native forest dominated by holm and cork oaks (*Quercus ilex* L., *Q. suber* L.) and other Mediterranean sclerophylls. This belt of natural vegetation and reforestations along the shoreline is used for protecting the agricultural crops of the large farm behind them from the sea wind rather than for producing timber. It is also used by the farm owner for recreation.

By thinning from below, the type of management should favour the formation of sparser pine stands and the re-establishment of a layer of oaks with the aim of creating a mixed and multi-stratified stand structure. In this way, the natural layout of the landscape will be accentuated on a stretch of coast where the dune vegetation before the forest appears to be well preserved and recreational activities do not affect the stands.

Cluster 3 includes medium-sized and regularly-shaped patches of adult stone pine reforestations, occasionally mixed with Aleppo pines (*Pinus halepensis* Mill.) situated in a rather anthropized landscape. In the largest buffer most of land is used for agricultural purposes, while in the narrow buffer there are also some holiday homes that have already been built or are under development close to the pine stands as well as patches of pinewood campsites. The pinewoods in this cluster are mainly owned by collective municipal administrative authorities responsible for granting land use rights to dwellers (*Università Agrarie*). As regards the stone pine forests, these rights are currently no longer claimed by the population, however the proprietors must ensure that the management of the asset still reaps benefits for the local community such as using the pinewoods to protect the crops from the sea wind in the immediate inland and to support sustainable tourist activities. Since the entire surface of the pine patches does not need to be accessible to the general public, an understory of Mediterranean broadleaf species can be enhanced either through uniform thinning or creating small openings in the pine canopy. Educational-recreational pathways can be used by the public to access the beaches. The management can be further differentiated in order to favour a denser, homogeneous, single-layer structure in the sectors bordering the agricultural areas in order to guarantee protection from sea wind. Towards the sea where the pinewoods are in contact with dune vegetation, greater diversity of tree composition and vertical stand structure could be adopted.

Cluster 4 consists of a group of medium-sized adult and mature pine forest patches that are mostly privately owned. Compared to cluster 3, both the narrowest and the widest buffer areas are mainly used for agriculture with some urbanized portions but are not in proximity to tourist-recreational structures. Some patches have greater naturalistic value, are included in Natura 2000 sites and towards the sea they are linked to strips of prostrate pine forest that connect them with the dune vegetation.

For the largest patches in this cluster, we propose a silvicultural treatment aimed at regenerating pines in gaps of approximately 1000 m^2 in order to obtain a more diversified structure (e.g., uneven-aged stands by small groups), releasing a ten-meter-wide strip of dense stand along the borders with agricultural crops. This type of pinewood management is aimed at achieving more complex forest systems within the Natura 2000 sites and differentiating the landscape by breaking the uniformity of the even-aged pine forest cover.

The patches included in Cluster 5 form a long, narrow strip of adult pinewoods, which is divided into irregularly-shaped small groups of pines (very low A/P ratio). The pines were sown in the middle of strips of shrubby and tree Mediterranean sclerophylls which quickly developed after reforestation and now function as dense connective tissue between the pine patches. The landscape in the wider buffer is composed of private farms while some holiday resorts (residences and campsites) have been built just behind the strip of forest vegetation. The forest areas are publicly owned and mainly found in a Natura 2000 site since the dune vegetation in front of the woody belt is deemed to be worthy of biodiversity protection.

Due to the reduced width of the pine forest strip, the poor accessibility to the stands, the need to guarantee the protection of the crops from the wind and limit the disturbance of dune vegetation, the pine forests should be allowed to co-evolve naturally with the Mediterranean broadleaves. Only trees at risk of failure along the paths will be cut in order to enable bathers to reach the beach safely.

The area of the pinewood clusters and the number of patches that compose them are shown in Table 6 and Figure 4.

Table 4 Conditioned frequencies analysis of the variables expressing management constraints, used for pine reforestations clustering.

Variable		Clusters 1	2	3	4	5	Mean value
Pinewood forest types	Belt pinewoods	0.0	20.0	0.0	0.0	0.0	1.5
	Mixed with *P. halepensis*	0.0	0.0	14.3	0.0	0.0	2.9
	Prostrate pinewood	0.0	0.0	0.0	7.1	0.0	1.5
	Pure even-aged	100	80.0	85.7	92.9	100	94.1
Included in a Natura 2000 SCI	No	85.7	100	100	64.3	7.1	52.9
	Yes	14.2	0.0	0.0	35.7	92.9	47.1
Use of stand as campsite	No	28.6	100	92.9	100	100	91.2
	Yes	71.4	0.0	7.11	0.0	0.0	8.8
Ownership type	Public	57.1	0.0	0.0	0.0	92.9	44.1
	Private	14.3	100	7.1	78.6	7.1	29.4
	Collective	28.6	0.0	92.9	21.4	0.0	26.5
Stand age	<30	0.0	0.0	7.1	14.3	0.0	4.4
	30<age<55	28.6	0.0	78.6	35.7	96.4	66.2
	>55	71.4	100	14.3	50.0	3.6	29.4
Pine patch size (ha)	<0,5 ha	0	0.0	0.0	0.0	57.1	23.5
	0,5<ha<1	14.2	0.0	0.0	0.0	25.0	11.8
	1< ha<5	28.6	20.0	71.4	100	14.3	45.5
	5<ha<10	14.3	60.0	28.6	0.0	0.0	11.8
	10<ha<20	28.6	20.0	0.0	0.0	3.6	5.9
	>20 ha	14.3	0.0	0.0	0.0	0.0	1.5
Area/ perimeter ratio (A/P)	<5	0.0	0.0	0.0	0.0	14.3	5.9
	5<A/P<10	0.0	20.0	7.1	7.1	64.3	30.9
	10<A/P<25	28.6	20.0	7.1	42.9	17.9	22.0
	25<A/P<50	28.6	60.0	64.4	50.0	3.5	32.4
	50<A/P<100	28.6	0.0	21.4	0.0	0.0	7.3
	>100	14.2	0.0	0.0	0.0	0.0	1.5

Table 5 Conditioned frequencies analysis of the variables expressing management constraints, used for pine reforestations clustering.

Buffer	Rank of naturalness	Clusters 1	2	3	4	5	Mean value
100 m Towards inland	1	14.3	0.0	14.3	0.0	10.7	8.8
	2	14.3	0.0	0.0	0.0	0.0	1.5
	3	28.6	0.0	0.0	0.0	0.0	2.9
100 m Towards inland	4	14.3	0.0	14.3	7.1	3.6	7.3
	5	0.0	0.0	28.6	78.7	10.7	26.5
	6	28.5	0.0	0.0	0.0	0.0	2.9
	7	0.0	0.0	14.3	7.1	21.4	13.2
	8	0.0	0.0	28.5	7.1	25.0	17.7
	9	0.0	20.0	0.0	0.0	25.0	11.8
	10	0.0	80.0	0.0	0.0	3.6	7.4
500 m Towards inland	1	0.0	0.0	0.0	0.0	0.0	0.0
	2	14.3	0.0	14.3	0.0	25.0	14.7
	3	28.6	0.0	0.0	0.0	3.6	4.4
	4	57.1	0.0	7.1	35.7	21.4	23.5
	5	0.0	0.0	35.7	57.1	10.7	23.5
	6	0.0	0.0	0.0	0.0	32.1	13.2
	7	0.0	0.0	42.9	0.0	3.6	10.3
	8	0.0	0.0	0.0	7.2	3.6	3.0
	9	0.0	100	0.0	0.0	0.0	7.4
	10	0.0	0.0	0.0	0.0	0.0	0.0
100 m Towards the sea	1	14.3	0.0	0.0	0.0	0.0	1.5
	2	42.8	0.0	0.0	14.3	3.6	8.8
	3	14.3	0.0	0.0	0.0	0.0	1.5
	4	0.0	0.0	0.0	0.0	0.0	0.0
	5	0.0	0.0	0.0	14.3	0.0	2.9
	6	0.0	0.0	0.0	14.3	0.0	2.9
	7	00	0.0	0.0	7.1	7.1	4.4
	8	14.3	0.0	50.0	0.0	3.6	13.2
	9	14.3	20.0	7.1	35.7	85.7	47.1
	10	0.0	80.0	42.9	14.3	0.0	17.7
500 m Towards the sea	1	0.0	0.0	0.0	0.0	0.0	0.0
	2	42.9	0.0	0.0	0.0	0.0	4.4
	3	0.0	0.0	0.0	0.0	0.0	0.0
	4	0.0	0.0	0.0	0.0	0.0	0.0
	5	0.0	0.0	0.0	0.0	0.0	0.0
	6	0.0	0.0	0.0	7.1	0.0	1.5
	7	0.0	0.0	0.0	7.1	0.0	1.5
	8	0.0	0.0	14.2	14.3	0.0	5.9
	9	14.2	0.0	42.9	0.0	7.1	13.2
	10	42.9	100	42.9	71.4	92.9	73.5

Table 6 Area covered by the reforestation groups defined by cluster analysis.

Cluster	Area (ha)	(%)	N° of patches	(%)
1	76.5	32.2	7	10.3
2	33.0	13.9	5	7.4
3	58.2	24.5	14	20.6
4	40.9	17.2	14	20.6
5	29.1	12.3	28	41.2

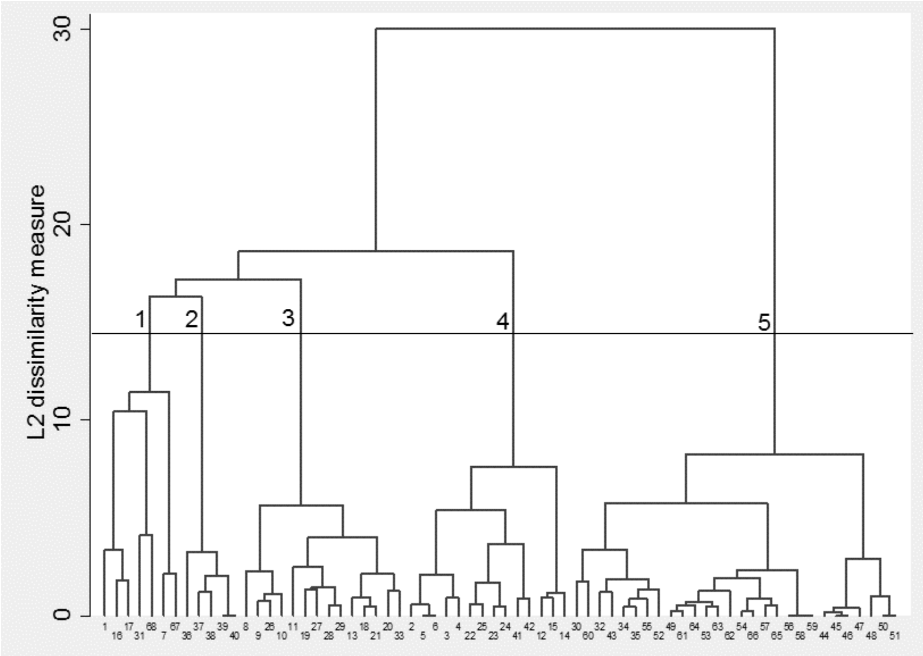

Figure 3 Dendrogram resulting from cluster analysis (different numbers identify different pinewood patches).

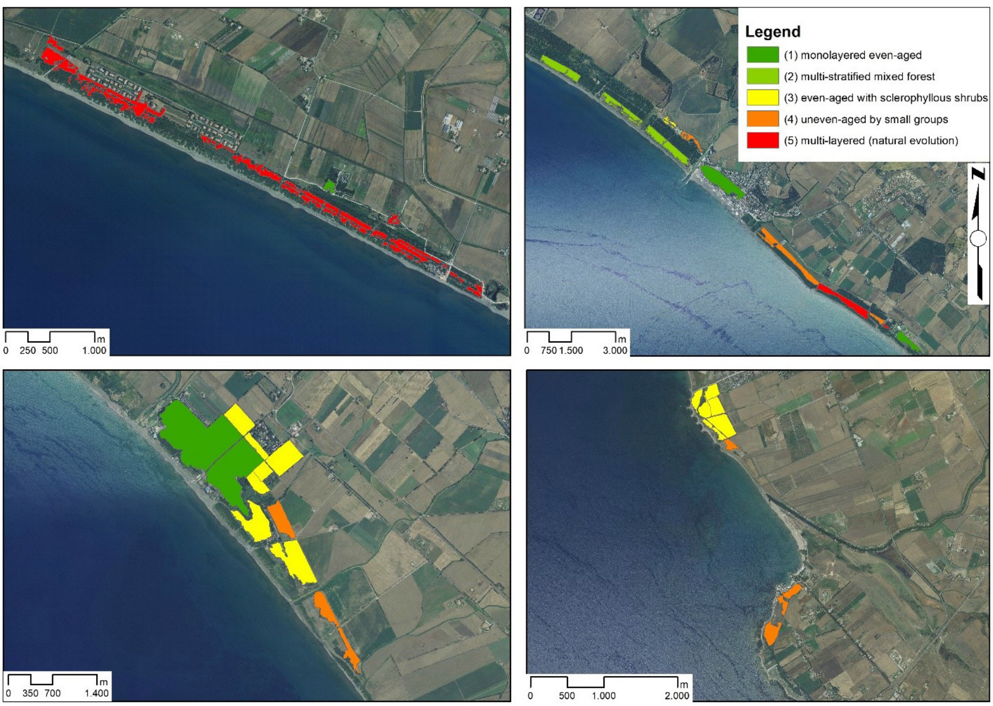

Figure 4 Mapping of the five reforestation clusters. The number of the cluster is reported in brackets in the legend together with the proposed stand structure for each pine patch.

Discussion

Most of the stone pine reforestations along the Viterbo province coastal area maintain a uniform stand structure due to dense sowing or planting in rows. Intensive timber and fruit-oriented management, based on clearcutting and artificial regeneration, are usually designed to maintain homogeneity, characterised by small differences in the size and age of the trees within the stands. However, this simplified structure contrasts with the opinion of several authors concerning the need to enhance the complexity of the stand structure in order to improve the resilience and adaptability of forests against the effects of global change (Millar et al. 2007, Puettmann 2011, Messier et al. 2014, O'Hara 2014, Nocentini et al. 2017, Messier et al. 2019, Nocentini et al. 2021). Furthermore, these stone pine reforestations currently grow in a rather diversified landscape and some have been enclosed in the urban fabric of the resorts that were built around them. Others are part of coastal dune vegetation systems that are still well preserved and some of the pinewoods have been granted priority habitat status according to the EU Directive 92/43/EEC. There are also some pine stands that, although located in a rural context, have favoured the creation of tourist facilities (campsites, resorts) at the edge of or within the reforestations. In many parts of the coastline, the pine stands protect agricultural crops from the sea wind and stabilise the sand dunes, the functions for which they were originally designed. Therefore, future forest management should consider this complex multifunctionality by adapting silvicultural interventions to the main functions of the pinewoods.

The main aim of this research was to propose a methodology to distinguish and group the pine forest patches in the study area according to the main features of the stands and the land uses surrounding them, by combining GIS analysis and statistical methods. The results confirmed that all the considered variables significantly discriminate the various groups of pinewoods although they are characterised by the same stand structure.

Land use classes within both buffer areas around the pinewoods well differentiate the clusters. The buffer analysis was successfully applied to evaluate landscape change around protected areas and cities (e.g., Gasparella et al. 2017). It provides landscape and urban planners with important information such as dynamics of land use change and landscape structure around natural resources. Buffers were used in our study to describe land use that directly affects the patches of pinewoods, thus contributing to identify the main functions and the most desirable management options for each group of reforestations.

The results confirmed that within a relatively small territory it is possible to manage coastal pine forests in various ways, thus reducing tradeoffs in the provision of various benefits, which is in line with the results of previous studies conducted on wider landscapes and on other forest types (Krcmar et al. 2005, Diaz-Balteiro & Romero 2008, Küçüker & Başkent 2015, Başkent 2018, Dong et al. 2018).

In pine forests in which it is essential to maintain the monoplane structure, timely tree thinning and removing dead branches are the main silvicultural interventions to perform to keep the trees healthy thus allowing the released pines to increase stem and crown diameter and assume the characteristic umbrella shape over time. In many patches, thinning has not been carried out despite the high stand density therefore the pinewoods are overcrowded with intertwined crowns and numerous dead branches. The positive effect of thinning on the diameter and crown growth of stone pines is known in literature (e.g., Loewe Muñoz et al. 2015, Mechergui et al. 2017), however most studies refer to younger stands than those considered in our research. The impact of thinning on the visitor's perception of stand recreational value is also debated (Beckwith et al. 2010). This potential tradeoff means that we should act with caution and frequently check the effect of the treatments on the stands and the reaction of the users. The intensity and localization of thinning within a pine stand also depends on the amount of space to leave for the development of sclerophyllous species in the lower layer, whether the objective is to ensure the accessibility of the entire pine forest (campsites, recreational areas) or only to gain access to specific pathways for walks or to reach the beaches.

Where the surrounding landscape is not strictly urbanized and there are fewer leisure and tourism activities in the pinewoods, pure even-aged stand structures can be gradually transformed into more open and multilayered stands composed of more cohorts of pines.

Multi-aged, complex structures can be realized if natural regeneration occurs, but this cannot be so easily achieved in the case of stone pine stands, mainly due to climate change (Manso et al. 2013, Calama et al. 2017) and invasive pests affecting cone production such as *Leptoglossus occidentalis* which has been detected along the Thyrrenian coast for many years. In the past, this issue has led many forest managers to prefer artificial regeneration-based silviculture models, including strip clearcuttings (Gordo 1999). However, selective cutting of large groups is known to be effective in stimulating the natural regeneration of other species of pines (Zhu et al. 2003) and these techniques have been applied in other pinewoods along the Thyrrenian coast (Ciancio et al. 1986, Agrimi et al. 2002, 2005, Ciancio et al. 2009) and in Spain (Butler et al. 2000, Barbeito et al. 2008) though seldom on a wide scale. Maintaining groups of pines of over 120 years old, controlling the competing sclerophyllous vegetation, reducing the intensity of regeneration fellings and scheduling them a few years after the occurrence of favourable recruitment events, are also recommended to reduce the probability of regeneration failure (Manso et al. 2012, 2013).

Pine stands are deemed to be “safe sites” for oak establishment (Sheffer 2012). Where the pine reforestations have grown in contact with residual strips of Mediterranean oak forests (cluster 4), they can enhance the re-establishment of broad-leaved trees and evolve towards mixed formations. Thinning can facilitate the colonization process. Contrastingly, the pines could spread into neighbouring oak forests in the event of fires.

Non-intervention is included among the management options that can be applied to pine reforestations, at least in the short-medium term. This option is suitable for the fifth cluster composed of small pine stands in close contact with sclerophyllous vegetation. They are classified as priority habitats as they are inserted as back dune forest vegetation in a well-preserved dune system (Carboni et al. 2009) so it is advisable to avoid the disturbance that any harvesting would cause. Passive methods are more successful than intensive interventions and are far less costly for achieving the full recovery of the degraded forest vegetation over time if soil conditions allow it (Chazdon 2008).

It is important to note that our analysis is aimed at providing guidelines to support planning at landscape level that should be verified at forest stand level. Flexibility is also required when applying silvicultural treatments including rotation length (Manso et al. 2013) and when planning future management interventions according to a systemic approach (Nocentini et al. 2017, 2021). These methods are compatible with the general recommendations for adaptive silviculture in Mediterranean forests in the climatic change context (Lindner et al. 2008).

The pine forests under study are no longer productive, which creates uncertainty regarding the economic framework of forest management that this study proposes. *Pinus pinea* wood has a limited market in the region. Cone and nut production are decreasing and badly organized and therefore do not provide enough income to the pinewood owners, which is common throughout the Mediterranean basin, where timber production is no longer the main function of many reforestations of different pine species such as *Pinus radiata* (Pignatti et al. 2021) and *Pinus nigra* (Fagarazzi et al. 2021). Contrastingly, the ecosystem services offered by the pine reforestations (e.g., leisure, tourism and windbreaks) support the economic sector and are important for the territory. The pine forests in the Viterbo coastal area were established starting from the 1930s and large amounts of labour and capital and innovative silvicultural techniques were required to restore a harsh and degraded environment. Today they represent a significant natural capital to be managed efficiently so that it continues to produce multiple benefits for the territory and its residents (Paquette & Messier 2010). This would justify the investment of funds by the owners and other stakeholders to carry out the above-mentioned management interventions. Another option would be to secure public and European funding in consideration of the two Natura 2000 sites and due to the importance of safeguarding the residual edges of coastal natural environments.

Conclusions

This study showed that the variety of land uses in the landscape mosaic of a coastal area can offer effective inputs to differentiate the management of forest systems. This approach is particularly useful in the case of homogeneous stands such as the Mediterranean stone pine reforestations under consideration and would enable us to achieve greater variety and resilience in the landscape over time while respecting the ecosystem services required of forest systems.

There are various ways to restore coastal forest vegetation. Mediterranean pine reforestation has been commonly used in Italy as it quickly achieves good results and provides numerous benefits for the territory. From a naturalistic point of view the stone pine forests in the study area cannot be considered a natural ecosystem according to the classification by Hobbs et al. (2009) as the species was established along the Lazio coast at the end of the 18^{th} century. However, it cannot be considered an extraneous species to the Mediterranean coasts. Together with oaks and other species of the Mediterranean maquis, *P. pinea* forms rather hybrid systems (Sheffer 2012) whose ecological traits should be carefully analysed to make their multifunctional management more effective.

However, the quality of the landscape around natural coastal vegetation is essential for its conservation. A responsible land use policy would help to reduce human pressures on residual ecosystems (Gasparella et al. 2017) and improve their state of health regardless of specific silvicultural management.

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Authors´ contributions

LP, AT, and MA conceived the idea and the structure of the article and wrote the main corpse of the text; AT, SB, WM, AA, compiled and prepared the dataset for the different forest patches. AT carried out the statistical analysis. AT and WM performed the GIS analysis. Funding acquisition by MA. All authors contributed to the definition and discussion of forest management proposals, read, and approved the final manuscript.

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