STAND STRUCTURE AND NATURAL REGENERATION IN A COASTAL STONE PINE (*PINUS PINEA* L.) FOREST IN CENTRAL ITALY

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Abstract – In Italy, Stone pine forests (*Pinus pinea* L.) have traditionally been cultivated to produce both wood and pine nuts. To this end, forest management is based on even-aged stands and the clearcut system with artificial regeneration. However, in the last decades Stone pine forests have become even more important for their social and cultural role, as well as for landscape conservation, especially those included within protected areas along the coast. For this reason, it is important to investigate whether the traditional silvicultural system is the most appropriate to achieve the current public needs or if there is a need to shift to more sustainable and close-to-nature silvicultural methods based on natural regeneration. Despite the relevance of this topic, in Italy few studies have focused on natural regeneration of Stone pine. This study was carried out in the Regional Park of Migliarino, San Rossore and Massaciuccoli (Tuscany, Central Italy) where we found natural regeneration of Stone pine in an even-aged stand of pine. The objectives of our study were (1) to characterize the forest structure of the Stone pine stand and (2) to quantify the natural regeneration of pine.

Our results show that natural regeneration of *Pinus pinea* L. in the Park of San Rossore is a reachable target, however an adequate management is needed. The results are discussed with the intention of providing knowledge to support management of Stone pine forests along the Tyrrhenian coast.

Introduction

In the Mediterranean basin Stone pine (*Pinus pinea* L.) forests cover more than 0.7 million ha [1], mainly in Spain, Portugal, Turkey, and Italy, offering a variety of products and functions.

The *Pinus pinea* forests have stabilized dunes and protected agricultural lands from sea winds; provide wood products and pine nuts, a highly valued product by the food industry; support production of other non-wood products, such as turpentine and truffles (*Tuber borchii* Vittad.); offer pasture and shelter for sheep and cattle. In addition, Stone pine forests offer valued recreational uses and provide habitats for plant and animal species of

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conservation interest, explaining why these forests are often included into sites of the Natura 2000 network [1, 2, 3, 4, 5] as an important component of the habitat 2270* Wooded dunes with *Pinus pinea* and/or *Pinus pinaster*.

Stone pine forest stands are mostly of artificial origin and usually present even-aged structures with a rotation length ranging between 80 and 120 years depending on site index. Traditional even-aged stand management in *Pinus pinea* is based on clearcuttings, which was maintained up to the end of the decade of 1970's [6] and then replaced with the uniform shelterwood system to get a close-to-nature regeneration system [5, 6, 7]. However, selection cutting with diametrical criteria is fairly widespread in multiaged complex structures [2, 8].

In Italy, the surface area of Stone pine forests amounts to 46290 ha, of which 11201 ha are in Tuscany [9], characterizing the coastal landscape for approximately five centuries, and providing important goods and services that have contributed to the socio-economic development of the area and also to the wellbeing of the inhabitants [10].

In Italy, the forest management system for Stone pine forests is still based on clearcutting with artificial regeneration used to optimize the production of seeds and/or wood. Today, this system is considered to reduce the environmental and landscape quality, and is often cause of conflicts, especially in protected areas and landscapes. This is one of the reasons behind a lack of active management of coastal Stone pine forests in recent decades, which brought forest owners and managers to ask for new silvicultural models [10, 11].

Therefore, it is important to investigate whether the traditional silvicultural system applied in Italy is the most appropriate one to achieve the current public needs or there is a need to shift to more sustainable and close-to-nature silvicultural methods based on natural regeneration.

Despite the relevance of this topic and the relative availability of phytosociological data from relevés in *Pinus pinea*-dominated forest across the Mediterranean [12], in Italy little information is available on natural regeneration of Stone pine and only few studies have focused on this issue [13, 14, 15, 16].

Accordingly, the objectives of our study were (1) to characterize the forest structure and (2) to quantify the natural regeneration in an even-aged coastal Stone pine forest in Central Italy.

Materials and methods

The study was carried out in Tuscany, in the Regional Park of Migliarino, San Rossore and Massaciuccoli (Central Italy). The Park hosts historical coastal Stone pine forests, which are included in the Natura 2000 site Selva Pisana (IT5170002). Forest structure consists of a composite of even-aged pine stands with a vertical structure comprising one or two canopy layers. Forest management is based on clear cutting with a rotation age of 90 years, and the regeneration is achieved artificially through plantations (or direct seeding as it was done in the past).

In the forest unit 27 (Lat 43.745690°, Long 10.294118°), we found an even-aged 103 year old *Pinus pinea* stand with natural regeneration of pine, which was selected as study area. This area is characterized by sandy soils, with average annual rainfall of 932 mm and average annual temperature of 14.8 °C, with maximum temperatures of 23.2 °C in July and a minimum of 7.1 °C in January [17]. The shrub layer was scarce, with a height ranging between 1 m and 2 m.

In the study area, field works were carried out in 2020 in three experimental plots (50x100 m), hereinafter referred to as A, B, and C (Figure 1).

Figure 1 – Study plots A, B and C.

In each plot, the x,y coordinates of all trees with height > 20 cm were recorded using a Topcon total station and a Global Navigation Satellite Systems (GNSS) Trimble Geo 7x dual frequency receiver, observing the pseudorange of both GPS and GLONASS; the recorded GNSS positions were post-processed with correction from a base station into a sub-meter precision.

For trees with a diameter at breast height (DBH) > 2.5 cm, the DBH, the total tree height (H), crown length and crown projections (four perpendicular radii along north, east, south, and west directions) were measured.

For trees with a DBH < 2.5 cm (i.e., the regeneration), the diameter at the base of the stem and H were collected.

The stand structure was characterized using the following structural indicators: number of stems (N), basal area (BA), wood volume (V, from NFI double entry volume equations [18]), quadratic mean diameter (QMD, the diameter of the mean basal area tree); dominant height (DH, the mean height of the 100 trees per hectare with the largest diameters), standard deviation of DBH (SDDBH), standard deviation of H (SDH), and canopy cover (CC); CC was computed modelling the shape of the crown as a circle with a radius equal to the arithmetic mean of crown projections measured in the field. The vertical structure (number of strata) was assessed using the TSTRAT function, which defines strata based on an assumption related to a competition cut-off height among tree crowns in a given area [19].

For natural regeneration, we computed N and the frequency of seedlings (NSE, 20 cm < H < 130 cm) and saplings (NSA, H ≥ 130 cm) [8], the arithmetic mean of diameters (MD) and H (MH), the standard deviation of diameters (SD) and SDH, and the regeneration index (RI) of Magini [20]. In addition, we used the Ripley's *K* function (bivariate L-function) to assess the spatial relationships between the regeneration and parent trees with DBH > 2.5 cm using the Programita software [21]. The bivariate L-function ($L_{12}(r)$) was computed for distances (r) ranging between 1 m and 25 m. To test the significance of deviation from null hypothesis of spatial independence between the regeneration and parent trees we adopted a 95 % confidence interval from the toroidal shift null model. In case of attraction between the regeneration and parent trees, $L_{12}(r)$ is greater than the confidence interval; in case of repulsion $L_{12}(r)$ is lower than the confidence interval; in case of spatial independence $L_{12}(r)$ is within the confidence interval.

Results

Stand structure

The structural indicators computed for each plot are reported in Table 1 and the stem number–diameter class distribution is shown in Figure 2.

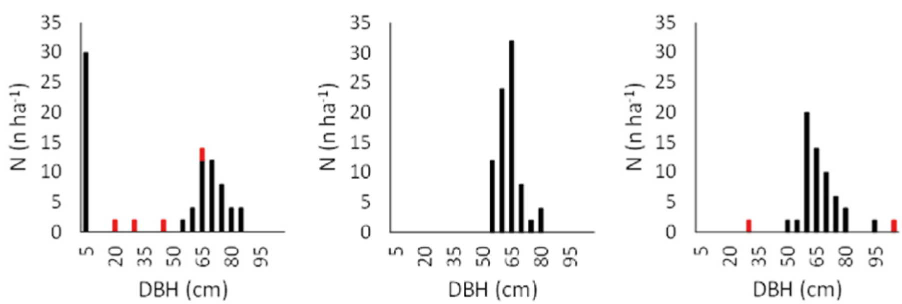
Plot B was a pure stand of *Pinus pinea*, while in plots A and B some scattered trees of *Quercus ilex* L. were found (Figure 2). In plots B and C, the shrub layer (*Erica scoparia* L.) was scarce, with a cover < 10 %; in plot A, shrubs were absent.

In plot A, wood volume (V), basal area (BA), and canopy cover (CC) were lower than in plots B and C. Indeed, in plot A, where the number of stems was similar to that found in plot B and larger than in plot C, the 36 % of the stems fell in the 5 cm diameter class, which was not represented in plots B and C (Figure 2). The dimensional variation in diameters and heights (SDDBH and SDH) were also higher in plot A than in plots B and C due to young trees of pine in the 5 cm diameter class.

The number of vertical strata was three in plot A (cut-off heights for strata 1, 2, and 3 = 22.3 m, 7.7 m, and 1.8 m, respectively) and two in plots B (cut-off heights for strata 1 and 2 = 22.1 m and 18.0 m, respectively) and C (cut-off heights for strata 1 and 2 = 20.0 m and 7.2 m, respectively).

Table 1 – Structural indicators for each plot.

Plot	N n ha^{-1}	BA m^2 ha^{-1}	V m^3 ha^{-1}	QMD cm	DH m	SDDBH cm	SDH m	CC %
A	84	19.2	283.3	53.9	26.9	32.2	12.8	58
B	82	26.1	365.7	63.7	26.4	5.9	3.2	78
C	64	23.1	315.8	67.9	26.8	12.9	4.0	71



A B C

Figure 2 – Stem number–diameter class (5 cm interval) distribution for each plot (*Pinus pinea* L. in black, *Quercus ilex* L. in red).

Natural regeneration

The stem density of the natural regeneration of pine varied between 362 trees ha^{-1} in plot C and 688 trees ha^{-1} in plot A.

Most of the regeneration was represented by seedlings (> 80 % in all plots) and the remaining by saplings. In plot A, where the density of the regeneration was higher than in plots B and C, the regeneration had a greater dimensional variation for diameters, as showed by SD. The regeneration index of Magini (RI) ranged between 3.1 in plot C and 6.3 in plot A (Table 2).

Table 2 – Characteristics of the natural regeneration of pine in each plot.

Plot	N	NSE	NSA	MD	MH	SD	SH	RI
	n ha^{-1}	%	%	cm	m	cm	m	
A	688	82	18	1.7	0.9	1.1	0.4	6.3
B	466	90	10	1.3	0.7	0.8	0.4	3.4
C	362	86	14	1.5	0.9	0.7	0.4	3.1

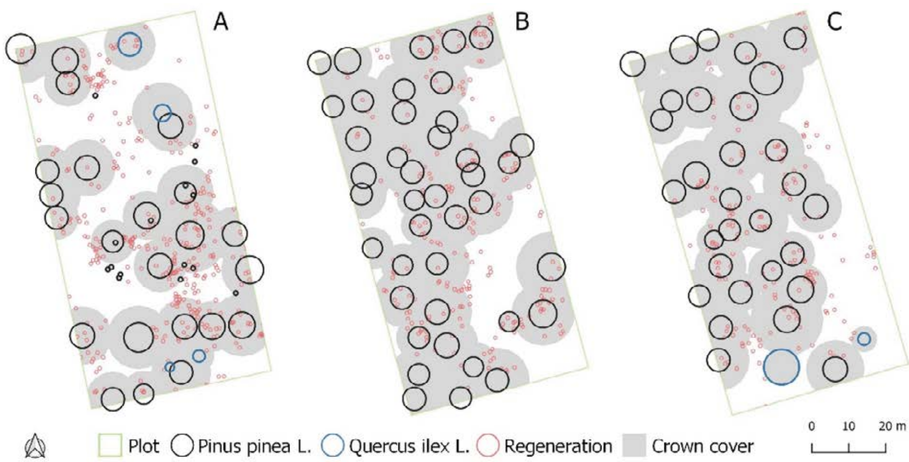


Figure 3 – Spatial distribution of trees in the plots (the circles are proportional to DBH, except for regeneration).

The spatial distribution of the regeneration within the plots was almost uniform, except for some areas corresponding to large openings in the canopy cover due to natural disturbances where regeneration was scarce. The frequency of the regeneration growing below the crown of adult trees was 72 %, 90 %, and 82 % in plots A, B, and C, respectively (Figure 3). This pattern indicates that the regeneration of *Pinus pinea* L. tends to grow within or nearby the influence area of the crown of parent trees, as can be expected from a tree species with heavy seed and a mainly gravity-based dispersal process [22]. Such pattern was confirmed by the results of the bivariate spatial point pattern analysis, which shows that the regeneration was aggregated to trees (DBH > 2.5 cm) in plot A at every distance considered (95 % confidence interval); in plots B and C, the pattern was aggregated at distances between 2 m and 10 m and between 3 m and 5 m, respectively, while the pattern was random at larger distances (Figure 4).

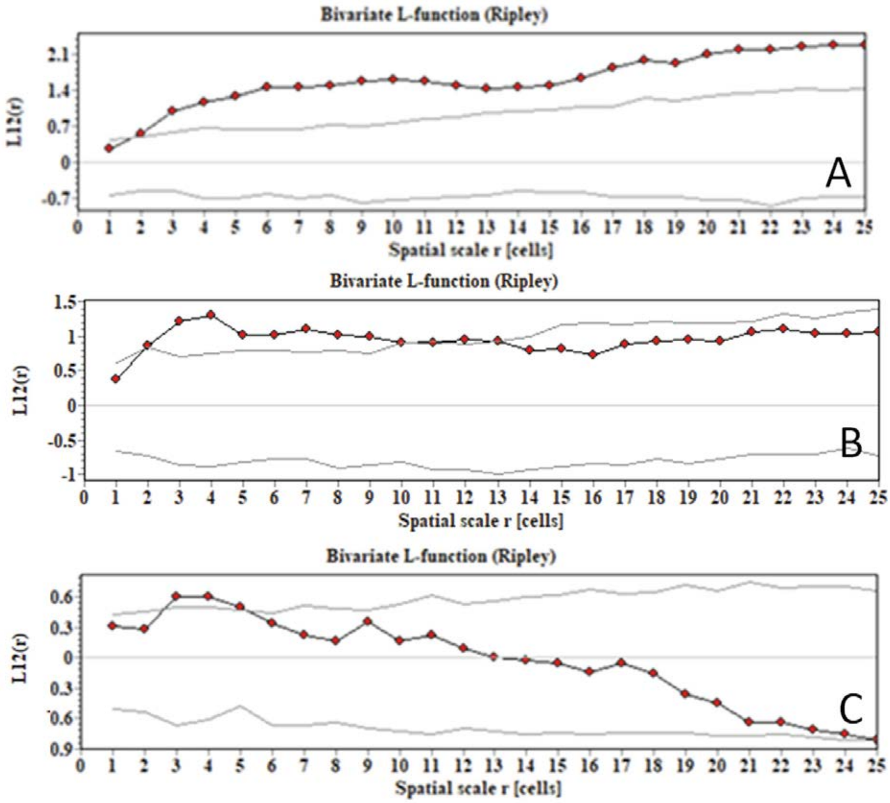


Figure 4 – Results of the bivariate L-function ($L_{12}(r)$) for distances (Spatial scale r) ranging between 1 m and 25 m used to assess the spatial relationships between the regeneration and parent trees with DBH > 2.5 cm. In case of attraction between the regeneration and parent trees, $L_{12}(r)$ is greater than the confidence interval (grey line); in case of repulsion $L_{12}(r)$ is lower than the confidence interval; in case of spatial independence $L_{12}(r)$ is within the confidence interval.

Discussion

The results of our study show that natural regeneration of *Pinus pinea* L. in the Regional Park of San Rossore is possible in pine stands with environmental conditions (e.g., light conditions) and structural characteristics similar to those found in the study plots.

In all plots, the stem number–diameter class distribution was typical of an even-aged stand structure, with wood volume, basal area and canopy cover lower in plot A than in plots B and C.

The highest density of regeneration was found in plot A. Here, the lower number of pine plants with DBH > 20 cm and a lower canopy cover than in plots B and C due to natural disturbances occurred in the past (e.g., lightning and windstorms) have probably favoured the germination of pine nuts and seedlings emergence. It is worth noting that the influence of lightning in opening gaps and encouraging Stone pine regeneration was also reported by [13] for a pine forest in the Regional Park of Maremma, in southern Tuscany.

In our study plots, most of the regeneration was represented by seedlings. However, the percentage of saplings ranged between 10 % in plot B and 18 % in plot A. In addition, in plot A, 36 % of pines with DBH > 2.5 cm were in the 5 cm diameter class (Figure 2), indicating that the regeneration dynamic is in progress.

The establishment of regeneration in *Pinus pinea* forests is affected by stand structure, which is the result of natural disturbances and the type of management carried out in previous years.

Calama et al. [23] found that the most favourable photosynthetic conditions for Stone pine seed dispersal, germination and seedling emergence are achieved in the mid-shaded positions, just below the area of the crown, at least in the initial stages of the regeneration process, although parent trees should be progressively removed to release the young pine trees as their light requirements increase. Aggregation of regeneration within or near to the area of crown influence is also explained by the limited seed dispersal capacity of Stone pine [8]. These findings are in accordance with what we observed in our study plots, where most of the regeneration was under the crown of adult trees (Figure 3) and the spatial pattern of the regeneration was aggregated to parent trees as indicated by the results of the point pattern analysis (Figure 4).

The studies of Manso et al. [24] and Calama et al. [6] report that the even-aged management practices used for the uniform shelterwood system may be behind the failure to support natural regeneration in Stone pine stands, particularly due to the low stand densities and large gap size occurring during the regeneration period. Indeed, due to incapacity to disperse seeds in large gaps created by intensive seed cut and secondary cuts, large areas remain without regeneration for years after the fellings. Although no cuts were carried out in our study area in the Park of San Rossore, at least in the last decades, this seems to explain the scarce presence of the regeneration in the large gaps occurring in plots A, B, and C (Figure 3).

Thus, to ensure seed arrival into gaps, thinning schedules should target to densities of about 125-150 stems ha^{-1} at the beginning of regeneration fellings, and intense fellings (e.g., intense uniform shelterwood system) should be replaced by more gradual fellings [6]. Simultaneously, it may be necessary to control the density of the understory vegetation [13]. However, as an alternative in those locations with abundant advanced regeneration, a shift towards uneven, multi-aged management by means of group selection system should be applied [8, 13, 14].

Conclusions

Natural regeneration-based silviculture has been increasingly regarded as a reliable option in sustainable forest management. However, successful natural regeneration is not always easy to achieve, especially in the Stone pine forests.

In the present study, we report the structural characteristics and the amount of natural regeneration found in a coastal *Pinus pinea* forest in the Regional Park of San Rossore, Central Italy, where regeneration has been historically unsuccessful.

Our results show that natural regeneration of *Pinus pinea* in the Park is a reachable target, although an adequate management is needed to support it. This means that the traditional silvicultural system based on clear cut should be replaced with more sustainable and close-to-nature silvicultural methods.

To this end, we encourage experimental cuts to favour advanced regeneration, by ensuring mid-shaded optimal conditions for seed germination and seedling survival in initial stages of the regeneration process, and preventing the creation of large gaps. Intensive fellings should be avoided and substituted by more flexible schedules, including e.g. shelterwood systems and group selection systems.

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