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Management of Maritime Pine: Energetic Potential with Alternative Silvicultural Guidelines

Teresa Fonseca and José Lousada

Abstract

The interest in the use of energy of the forests has been increasing in recent decades. Biomass has the potential to provide a cost-effective and sustainable supply of renewable energy. Moreover, it could be valuable for reducing the severity of forest fires and create employment in extremely needy regions. This chapter brings to discuss the effect of forest management on the potential of energy provided by the woodlands. The authors selected as a case study the management of maritime pine (*Pinus pinaster* Ait.), an important softwood species in the southwest of Europe and, in particular, in Portugal where it represents around 22% of the forest area. A summary of traditional and new silvicultural guidelines for the species, used or proposed to be followed at the national level, is presented. The study follows with the evaluation of stand yield and the potential of energy associated with four alternative silvicultural guidelines. Two scenarios follow traditional standards (an initial density of 1100–1200 trees/ha), while the other two consider managing a high density stand (an initial density of 40,000 trees/ha). Simulations were performed with the ModisPinaster model. The results show that the new designs provide a considerable yield in terms of biomass and energy.

Keywords: forest management, regeneration, thinning, fire, biomass, energy, CAPSIS

1. Introduction

The Portuguese forest occupies an area of 3224.2 thousand hectares, which represents around 36.2% the mainland area according to the Sixth National Forest Inventory (IFN6) report [1]. The major part of the forest areas (63.7%) refers to hardwood species in pure stands (mainly *Quercus* sp. and *Eucalyptus* sp.), followed by pure stands of softwood species (23.1%). Mixtures are less common occupying around 13%. Among the softwood species, maritime pine (*Pinus pinaster* Ait.) is the most represented species, covering an area of 713.3 thousand hectares, with a growing stock of 67 Mm³ [1]. The species is of great economic importance in the country. The pine sector represents 52% of the gross value added (GVA) and 46% of the turnover of forestry industries and accounts for 35% of the forest industry's exports of goods. Wood consumption amounted to 4.2 Mm³ in 2018, representing

an increase in around 10% compared to 2017 [2]. Primary use ranked by descending order according to consumption level is sawmill, pellets, panels, pulp and paper, poles, and pilings [2], and since 2016, the annual production of pellets in Portugal exceeds 1.4 million tons [3].

The impact of pests (the most significant being the nematode) and fire has contributed to a severe reduction in the area occupied with maritime pine forests with time. It is worthwhile to mention a decrease in 134.7 thousand hectares just from 2015 to 2018 [1] due to the impact of severe forest fires occurring in this recent period. The same source refers that the growing volume, potentially affected by the fires between 2016 and 2018, is 15.6 Mm³.

The recurrent menace of forest fire risk in Portugal, coupled to an increase in consumption of pinewood for a diversity of uses, has been driving for a new vision of forest management for these forests.

In the past, the use of shrubs and forest residues was extremely low, being limited to small domestic uses, without any representativeness at the industrial level. However, in recent years, due to the growing awareness of the use of natural, renewable, and sustainable energy sources, there has been a high pressure for the use of forest biomass for energy purposes. It is in this context that the need arises to discuss and test new types of silvicultural management that allows exploiting not only the woody component but also the forest residues and shrubs, to increase the profitability of the forest and decrease its susceptibility to fire.

In this chapter, a summary of traditional and new silvicultural guidelines for the species used or proposed to be followed at the national level is presented. The authors proceed with the evaluation of total biomass and the potential of energy for a set of four silvicultural models through simulation. Simulation of stand development was performed with the simulator ModisPinaster [4, 5].

Two of the models (Scenarios 1 and 2) follow the traditional standards of stand establishment (plantation or direct seeding) and management. The other models (Scenarios 3 and 4) are driven by the increase of forest areas with natural regeneration regenerated post-fire and the demand for the wood of small size, with higher densities at the establishment than the traditional standards. Results will provide valuable information for forest planning and decision support to forest managers of pine forest systems.

2. An overall view of the silvicultural guidelines for maritime pine in Portugal

2.1 Silviculture guidelines in traditional roundwood-oriented management

In Portugal, maritime pine traditionally develops in pure stands, with mixtures (e.g., with *Eucalyptus* sp., *Castanea sativa*, or *Quercus suber*) being less frequent [1].

The traditional silvicultural guidelines for the species consider the use of artificial regeneration by seeding or by plantation. For plantations and direct seeding, initial densities differ among the silvicultural models, ranging from around 1100 to 2800 trees/ha in the stand tables by Oliveira [6] and of 2300–2500 in the models developed by the authors of Refs. [7, 8]. Oliveira [9] suggested that when the aim is wood for industry, the plantation should be the preferable method with a stem density between 1250 trees/ha (in low fertility sites) and 1670 trees/ha (in better sites), with a minimum line distance of 3 m to enable the mechanization of future interventions.

Harvest age ranges from 40 to 50 years [7, 10, 11] to ensure that the age of absolute exploitability (age at which the production of woody material per unit area

is maximum) has already been reached, and the wood harvest has adequate dimensions to be classified as sawmill wood. The age of the final cut can occur at lower ages, such as 35 years, in sites of better quality [7], or be extended up to 80 years (e.g., [6, 8]), depending on the management objectives and aiming the target of log size.

Final density varies among the silvicultural models and with the prescriptions of density regulation as both by tree release or “precommercial” thinning set at young stand ages (e.g., 5 and 10 years) and by intermediate thinning at juvenile and mature development stages. In this section, we will focus on prescriptions of the later as those prescriptions are a major differentiating element in the traditional silvicultural models for the species. Intermediate thinning (categorized as “commercial” thinning) typically begins between 15 and 20 years and may last until 5–10 years to the harvest age. The thinning frequency is defined between short and medium (5–10 years), corresponding to a top height growth of 2–3 m [12]. Wilson’s spacing factor has been dictating the density regulation. The factor is defined as: $Fw = 100N^{-0.5}h_{dom}^{-1}$ [13], where h_{dom} refers to the dominant height defined as the average height (m) of the 100 thickest trees per hectare, and N indicates the number of trees per hectare, after thinning. Prescribed values of Fw range from 0.20 (moderate-low thinning) to 0.28–0.30 (very heavy thinning from below) [6–8, 14, 15].

Páscoa [16] suggests, in alternative to Fw , the specification of a residual area value for density regulation, while the authors of Refs. [10, 11] describe the thinning regimes in pine stands based on the removal of a specified percent range of the number of trees. The guidelines presented by the authors of Refs. [10, 11] consider a first thinning at the age of 15–20 years, with the removal of 20–40% of the trees. A second thinning should occur at the age of 25–30 years, with the removal of 20–30% of the trees and a third thinning at the age of 35–40 years, with the removal of 20–30% of the trees. The final density should be of 300–500 trees/ha.

Luis and Fonseca [17] proposed the rules based on the self-thinning theory and the stand density index [18], given as $SDI = N(dg/25)^b$, where b is the allometric coefficient (–1.897 for maritime pine), and dg is the quadratic mean diameter of the trees. Luis and Fonseca [17] hypothesized that 60 and 35% of SDI are appropriate values for the upper and lower limits of the optimum growth–density interval, respectively, and 25% is the reasonable value for the crown closure situation, for maritime pine in the Portuguese conditions.

Fonseca and Calçada-Duarte [12] proposed a new density regulation model under an adaptive management context, based on Wilson's spacing factor, $Fw = 0.21$. The model, given by $N = 18877 \exp(-0.656dg^{0.5})$, provides the optimal stand density, for a given mean diameter of the stand, that prevents the understory growth, thereby reducing the vulnerability to a forest fire and ensuring at the same time the highest values of stand yield.

2.2 Management of naturally regenerated post-fire stands

The impact of rural fire, in number and burnt area, along the recent decades, severely affected the forest cover and the age structure of the pine woodlands, leading to an increase in pinewoods in the early stages and juvenile stratum [1]. In areas naturally regenerated post-fire, density at the beginning of stand establishment can reach a far greater number than the figures of stand density registered in the traditional silvicultural models with artificial regeneration. In datasets used by Enes et al. [19] to identify the maximum attainable density trajectory at the early stages of development of the species, maximum values ranging from 7500 to 90,000 plants are reported in juvenile maritime pine stands (age less than 20 years)

in Portugal. The availability of naturally regenerated forest promotes harnessing the natural regeneration from seeds as an option that enables saving in site preparation and plantation costs. The management of these areas requires careful analysis and adaptations of traditional models to these “new” forest systems, namely for the ones growing at high density or overstocked levels. Two challenges immediately arise, one in terms of density regulation and the other about management objectives, especially concerning the size of wood produced.

Alegria [20] analyzed the alternative wood production-oriented silvicultural scenarios for maritime pine in Center of Portugal. For areas of natural regeneration, high initial stand densities of 3000 and 5000 trees/ha were selected for essay, with different density prescriptions, based on Fw spacing factor (0.25–0.28 and 0.20) and based on a crown competition factor of 100%. The alternatives analyzed consider two systematic precommercial thinnings at 5 and 10 years, three commercial thinnings from below at 15–20, 20–25, and 35–40 years, and final harvest at 45–50 years depending on the site index. According to the author, the model departing from an initial stand density of 3000 trees/ha and commercial thinning with Fw ranging from 0.25 to 0.28 was the most suitable for the existing naturally regenerated maritime pine stands of Portuguese private forest areas. Total stand volume was similar to the obtained with a traditional model ([6], with an Fw around 0.27) and showed to have a good balance between both round and pulpwood yields. However, pulpwood increased, comparatively of the traditional model.

In the essay conducted by Alegria [20], the age for the final cut was kept under the usual harvest age range (45–50 years). Due to the ongoing risk of forest fire, the managers have been discussing shortening the rotation length to 15–20 years. Exploratory essays in the field are under development, as communicated in technical meetings recently promoted by Centro Pinus (<https://centropinus.org/>) and sponsored by International Union of Forest Research Organizations (IUFRO, <https://www.iufro.org/>), but, to the best knowledge of the authors, there are no published results yet.

3. Materials and methods

This section is structured in two parts. In Section 3.1, the authors select and characterize a set of silvicultural models proposed for maritime pine and identify the new ones for evaluation of the potential energy purposes. In Section 3.2, the authors proceed with the introduction and general description of simulator used in the evaluation of stand growth and implementation of thinning and describe the methodology followed in the simulations.

3.1 Silvicultural scenarios

The case of study selected refers to alternative management of maritime pine, differing in terms of initial stand density, density regulation, and on the rotation length.

In Section 2.1, the authors presented a summary of the silvicultural guidelines that have been proposed for the maritime pine species in Portugal for roundwood production. As shown, the management of the species traditionally considers initial densities ranging from 1100 to 2800 trees/ha, and rotations of 35–50 years, with prescription of periodic thinning – typically based on Fw spacing factors – for reducing intratree competition and providing some economic return. The model proposed by Louro et al. [10], made available by the Institute for Nature and Forest Conservation (ICNF) in supporting documents for the elaboration of forest

projects, was selected to sustain the design of Scenario 1. This scenario considers a low density at stand establishment and focuses on wood production.

To the best knowledge of the authors, the density regulation model proposed by Fonseca and Calçada-Duarte [12] is the most recent proposal within the traditional vision of wood production-oriented silviculture in Portugal. The model applies to even-aged stands managed for roundwood production but at higher densities than the model by Louro et al. [10]. As the model explicitly takes into account the risk of a forest fire was selected as a basis to define Scenario 2.

Given the representativeness in Portugal of dense pinewoods regenerated post-fire, two scenarios (Scenarios 3 and 4) were additionally considered. These scenarios were specifically designed by the authors for areas with a high density of natural regeneration after fire. Both initialize with a density of 40,000 plants per hectare at the age of 8, which are supported by Almeida et al. [21] and corroborated by Enes et al.'s [19] findings on the size-density trajectory in regenerated pine stands after a fire. Scenario 3 considers a harvest age of 45 years as typically occurs in traditional management. In this scenario, it is intended not only to maximize the high biomass production aimed at energy purposes in the initial stage of the stands but also to obtain the wood quality in the remaining mature trees. In this way, the biomass generated by mechanical thinning of 3 m width strips from natural regeneration will be used in energy purposes. In the remaining trees managed at an early stage with high stand densities followed by heavy thinning operations, the height growth will be promoted to reduce the size and influence of the crown and, in this way, the amount of juvenile wood in the stem. Scenario 4 meets the intent of managing the pine forests in short rotations, mimicking “energy crops”. The material provided by this scenario will be used basically as biomass for energy, pulp, panels, or pilings.

The characterization of the four scenarios is depicted in **Table 1**. The prescriptions of treatments scheduled for the early stage of development in Scenarios 1 and 2 follow the traditional recommendations. Pruning was not included as it is not mandatory.

3.2 Simulation of stand growth and assessment of potential energy in the silvicultural scenarios with ModisPinaster

Simulators can provide valuable information to assess stand growth under different management regimes as they allow to easily essay various alternatives and provide immediate results on a set of variables that can be used to support management decision. In this study, we selected Model with Distribution of Diameters for *Pinus Pinaster* (ModisPinaster) as the appropriate simulator. ModisPinaster [4, 5] is an “easy-to-use” model, freely available for use at Computer Aided Projection of Strategies In Silviculture (CAPSIS, <http://www.inra.fr/capsis>) platform [22]. The model offers the flexibility of use in terms of input data needs (data from standard forest inventories), alternative density regulation approaches (manual or automatic prescriptions based on spacing factors and density indices, besides the usual density measures of the number of trees or basal area per hectare), and diversity of output information (volume, biomass, carbon, and energy), among other features. A comprehensive description is provided in Ref. [5]. In its general use, the model starts simulations at a minimum age of 12 years, following the restrictions of their internal modules. For specific purposes, such as in this case study, those restrictions can be punctually alleviated, providing starting points at lower ages (for further details, see [5]).

Table 2 presents a summary of the input data used in ModisPinaster to initialize the simulations for the selected scenarios. Scenarios 1 and 2 are initialized at the age of 12 for the simulation of stand growth before the first thinning, which occurs, in

| Year | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|-------|--|---|--|--|
| 0 | Site preparation | Site preparation | | |
| 0 | Stand establishment: artificial regeneration (plantation) 1100 plants/ha | Artificial regeneration (seeding or plantation) 2200 plants/ha | Natural regeneration. It is assumed a value of 40,000 plants/ha | Natural regeneration. It is assumed a value of 40,000 plants/ha |
| 7-8 | | | Release operation (8 yr). Reduction of stand density to 30,000 trees/ha through systematic (mechanical) thinning by 3 m width strips, leaving 1 m wide strips with trees | Release operation (8 yr). Reduction of stand density to 30,000 trees/ha through systematic (mechanical) thinning by 3 m width strips, leaving 1 m wide strips with trees |
| 3-10 | Control of spontaneous vegetation (3, 8 yr) | Control of spontaneous vegetation (3, 8 yr) | Control of spontaneous vegetation (8 yr) | Control of spontaneous vegetation (8 yr) |
| 8-12 | | | Thinning from below (12 yr). Removal of a. 60% trees/ha within the 1 m-wide strips with trees | Thinning from below (12 yr). Removal of a. 50% trees/ha within the 1 m-wide strips with trees |
| 15-40 | Three thinning from below (15, 25, 35 yr). Removal of a. 30% trees/ha per action | Three thinning from below (22, 29, 36 yr). <i>Fw</i> a. 0.21 after thinning | Four thinning from below (16, 20, 28, 36 yr). Removal of a. 35-40% trees/ha per action | Thinning from below (16 yr). Removal of a. 40% trees/ha |
| 15-45 | Final harvest at 45 yr | Final harvest at 45 yr | Final harvest at 45 yr | Final harvest at 20 yr |

Table 1. Characterization of the silvicultural models selected for the essay.

| Variable | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|--|-------------|-------------|------------|------------|
| Stand age (t , yr) | 12 (8) | 12 (8) | 8 | 8 |
| Site index (SI_{35} , m) | 20 | 20 | 20 | 20 |
| Number of trees (N , trees/ha) | 1100 | 2200 | 40,000 | 40,000 |
| Basal area (G , m ² /ha) | 8.8 (4.0) | 9.6 (3.0) | 19.6 | 19.6 |
| Quadratic mean diameter (d_g , cm) | 10.1 (6.8) | 7.5 (4.2) | 2.5 | 2.5 |
| Dominant diameter (d_{dom} , cm) | 16.4 (13.0) | 13.7 (10.0) | 8.0 | 8.0 |

Table 2. Summary of the input data used in ModisPinaster for initializing the simulations with the selected scenarios.

the traditional models, around the age of 15 years. For Scenarios 3 and 4, the initialization point was set to a lower age, to allow for the simulation of the first intervention, scheduled for the stand age of 8 years. To enable a comparison of values, estimated values of the stand variables at the age of 8, for Scenarios 1 and 2, are shown inside the parenthesis (**Table 2**).

The simulations consider stands developing in a site of high quality for the species, with a dominant height of 20 m at the reference age of 35 years, according to Ref. [23] site index (SI) model.

ModisPinaster allows simulating stand growth (in 1-year steps) and simulation of interventions. The prescription of thinning can be performed manually through the selection of the values of the number of trees to thin by diameter class or automatically using an algorithm of thinning. In the automatic procedure, the options include the specification of the number of trees to cut or to set the target values of the Wilson's spacing factor (Fw) or the stand density index (SDI) in a percentage scale. The simulator offers an extensive set of output information with detail of stand level or discriminated by diameter class. For this study, the authors selected as output, following the stand-level variables: total volume of the stem over bark, and total above-ground biomass (air-dried, assuming around 25–30% of moisture), carbon, and higher heating value (HHV). When a thinning occurs, the simulator also provides information on volume, biomass, carbon, and energy for the removed stand and the cut wood material residuals. For the current simulations, the biomass, carbon, and HHV values were estimated using the equations from Ref. [24], integrated into ModisPinaster.

The output information was registered for the years with scheduled interventions and for the harvest age accordingly to the description made in **Table 1**. Also, the estimates about the biomass removed in shrub control for release are provided. These estimates of understory component were calculated separately based on the research on average values of shrub biomass (air-dried, t/ha) made by Enes et al. [25].

4. Results and discussion

Tables 3–6 present the results of simulations performed with ModisPinaster for the silviculture guidelines described in **Table 1**, concerning Scenarios 1–4. The information presented in **Tables 3–6** refers to the characteristics of the material removed in each intervention (release, thinning, and harvest), quantified in total stem volume (V_r , m³/ha), aboveground air-dried biomass (B_r , t/ha), carbon (C_r , t/ha), and energy (E_r , GJ/ha), calculated on the base of HHV_r and the amount of biomass per hectare. The subscript “ r ” indicates “removed.” When an intervention

| t (yr) | Interv. | N_b (trees/ha) | N_r (trees/ha) | V_r (m ³ /ha) | dg_r (cm) | B_r (t/ha) | C_r (t/ha) | E_r (GJ/ha) |
|--------------------------------------|-----------------|---------------------|---------------------|-------------------------------|----------------|------------------|-----------------|--------------------|
| 3 | Shrubs release | – | – | – | – | (3) | (1) | (53) |
| 8 | Shrubs release | – | – | – | – | (7) | (2) | (137) |
| 15 | First thinning | 1100 | 330 | 12 | 10.3 | 11 (19) | 5 (9) | 212 (365) |
| 25 | Second thinning | 770 | 230 | 45 | 18.5 | 29 (36) | 12 (17) | 532 (635) |
| 35 | Third thinning | 540 | 160 | 95 | 26.7 | 54 (45) | 22 (21) | 990 (769) |
| 45 | Harvest | 380 | 380 | 432 | 38.5 | 238 (107) | 97 (34) | 4332 (1223) |
| Total (total forest residues) | | | | 583 | | 333 (217) | 136 (85) | 6066 (3181) |

Table 3.
 Characteristics of the yield from thinning and yield at harvest age, according to the simulation results obtained with Scenario 1.

| t (yr) | Interv. | N_b (trees/ha) | N_r (trees/ha) | V_r (m ³ /ha) | dg_r (cm) | B_r (t/ha) | C_r (t/ha) | E_r (GJ/ha) |
|--------------------------------------|-----------------|---------------------|---------------------|-------------------------------|----------------|------------------|------------------|--------------------|
| 3 | Shrubs release | - | - | - | - | (3) | (1) | (53) |
| 8 | Shrubs release | - | - | - | - | (7) | (2) | (137) |
| 22 | First thinning | 2200 | 787 | 39 | 10.1 | 30 (36) | 12 (17) | 537 (632) |
| 29 | Second thinning | 1413 | 508 | 67 | 14.6 | 42 (42) | 17 (20) | 757 (713) |
| 36 | Third thinning | 905 | 235 | 66 | 19.4 | 38 (49) | 15 (23) | 677 (826) |
| 45 | Harvest | 670 | 670 | 420 | 28.9 | 229 (139) | 92 (50) | 4135 (1155) |
| Total (total forest residues) | | | | 591 | | 338 (276) | 137 (113) | 6107 (3516) |

Table 4. Characteristics of the yield from thinning and yield at harvest age, according to the simulation results obtained with Scenario 2.

| t (yr) | Interv. | N_b (trees/ha) | N_r (trees/ha) | V_r (m ³ /ha) | dg_r (cm) | B_r (t/ha) | C_r (t/ha) | E_r (GJ/ha) |
|--------------------------------------|-----------------|---------------------|---------------------|-------------------------------|----------------|-------------------|------------------|---------------------|
| 8 | Tree release | 40,000 | 30,000 | - | - | (890) | (308) | (13,527) |
| 12 | Shrubs release | - | - | - | - | (3) | (1) | (65) |
| 12 | First thinning | 10,000 | 6000 | 45 | 3.8 | 115 (62) | 40 (29) | 1744 (936) |
| 16 | Second thinning | 4000 | 1600 | 27 | 6.5 | 35 (38) | 13 (18) | 594 (647) |
| 20 | Third thinning | 2400 | 840 | 35 | 9.3 | 28 (35) | 11 (17) | 502 (607) |
| 28 | Fourth thinning | 1560 | 470 | 59 | 13.9 | 36 (46) | 15 (22) | 657 (787) |
| 36 | Fifth thinning | 1090 | 380 | 107 | 18.9 | 60 (51) | 24 (24) | 1079 (841) |
| 45 | Harvest | 710 | 710 | 469 | 28.8 | 252 (139) | 102 (35) | 4549 (1201) |
| Total (total forest residues) | | | | 741 | | 527 (1219) | 205 (454) | 9125 (18612) |

Table 5. Characteristics of the yield from thinning and yield at harvest age, according to the simulation results obtained with Scenario 3.

is performed, the age of the stand (t, years) is provided along with the number of standing trees (N , trees/ha) before the intervention (N_b) and removed (N_r) and the quadratic mean diameter of the removed trees (dg_r , cm). Biomass, carbon, and energy of the forest residues are provided, within parenthesis, near to their counterparts of the removed material.

The distribution of trees per diameter classes, for the simulated scenarios, at harvest age is depicted in **Figure 1**. In **Figure 1**, the scale for the vertical axis in Scenarios 1 (S1) and 2 (S2) is larger than the scale used for Scenarios 3 (S3) and 4 (S4), due to the differences on the number of trees per hectare.

| t (yr) | Interv. | N_b (trees/ha) | N_r (trees/ha) | V_r (m ³ /ha) | dg_r (cm) | B_r (t/ha) | C_r (t/ha) | E_r (GJ/ha) |
|--------------------------------------|-----------------|---------------------|---------------------|-------------------------------|----------------|-------------------|-----------------|----------------------|
| 8 | Tree release | 40,000 | 30,000 | – | – | (890) | (308) | (13,527) |
| 12 | Shrubs release | – | – | – | – | (3) | (1) | (65) |
| 12 | First thinning | 10,000 | 5000 | 37 | 3.7 | 96 (78) | 33 (37) | 1452 (1162) |
| 16 | Second thinning | 5000 | 2000 | 27 | 5.9 | 18 (46) | 15 (22) | 682 (765) |
| 20 | Harvest | 3000 | 3000 | 154 | 11.1 | 118 (69) | 48 (26) | 2119 (933) |
| Total (total forest residues) | | | | 218 | | 232 (1086) | 96 (394) | 4253 (16,452) |

Table 6.
 Characteristics of the yield from thinning and yield at harvest age, according to the simulation results obtained with Scenario 4.

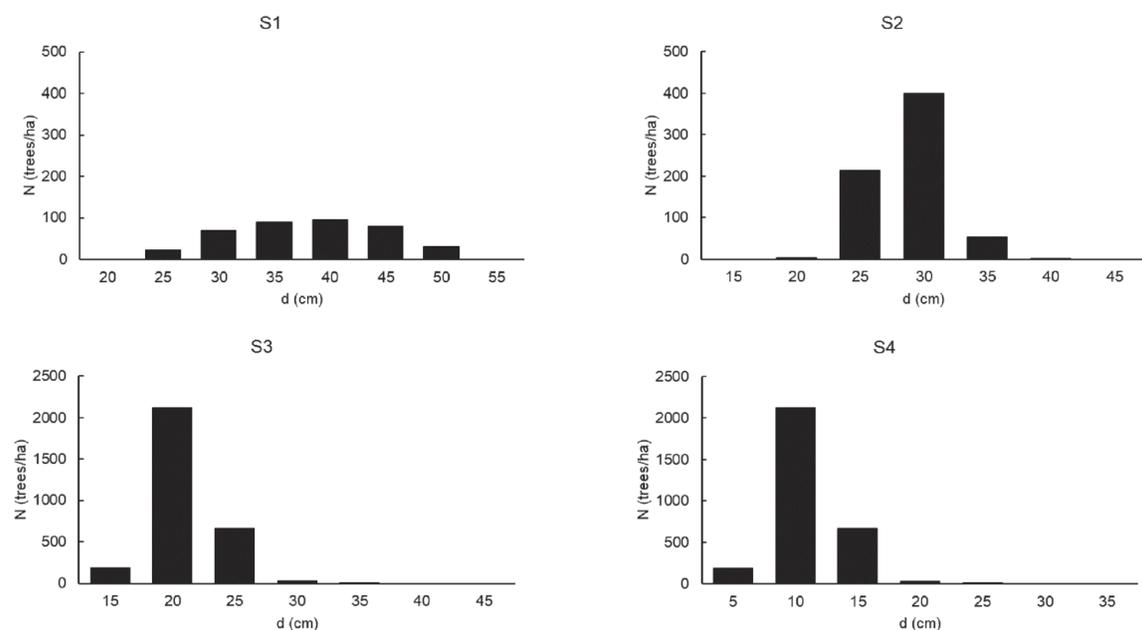


Figure 1.
 Diameter distributions per 5 cm classes at harvest age (45 years for Scenarios 1–3, and 20 years for Scenario 4).

A summary of the yield totals obtained at harvest age with the four scenarios is presented, for comparison purposes, in **Table 7**. The total yield reported as stand volume, biomass, carbon, and energy reflect the amount of yield obtained at the moment of harvest, plus the amounts obtained in silvicultural operations over stand rotation.

The percentage of differences among scenarios for the variables, mean diameter (dg), and total yield is displayed in brackets. Differences were evaluated using the values obtained with the silvicultural guidelines proposed in Scenario 3 as the basis for comparison. This scenario corresponds to a new management design, applicable to stand with a high initial density, which is intended to know the expected management results. It allows a direct comparison with Scenarios 1 and 2 (with the same rotation length) and with the alternative model described in Scenario 4, managed at lower rotation age.

Regarding Scenarios 1 and 2 (more traditional in Portugal), there were no notable differences between them in terms of yield. Both present similar volume (583

| Scen. | t (yr) | N_r (tree/ha) | dg_r (cm) | V_r (m ³ /ha) | B_r (t/ha) | C_r (t/ha) | E_r (GJ/ha) |
|-------|--------|--------------------|----------------------|----------------------------|--------------|--------------|------------------|
| 1 | 45 | 380 | 38.5 (+25%) | 583 (-27%) | 550 (-217%) | 220 (-199%) | 9247 (-200%) |
| 2 | 45 | 670 | 28.9 (\approx 0%) | 591 (-25%) | 614 (-184%) | 250 (-164%) | 9623 (-188%) |
| 3 | 45 | 710 | 28.8 | 741 | 1745 | 659 | 27,737 |
| 4 | 20 | 3000 | 11.1 (-159%) | 218 (-239%) | 1318 (-32%) | 490 (-35%) | 20,705 (-34%) |

Table 7.
Total yield at harvest age obtained with the four scenarios.

and 591 m³/ha), biomass (550 and 614 t/ha), carbon (220 and 250 t/ha), and energy (9247 and 9623 GJ/ha), although with a slight superiority of Scenario 2 for these total yields. In terms of tree size, the trees in Scenario 1 span for a large interval of diameter classes (**Figure 1**). Scenario 1 provides the higher average diameter at final harvest among the three essayed with a rotation of 45 years.

Scenario 3 presents much higher yield values (volume = 741 m³/ha; biomass = 1745 t/ha; carbon = 659 t/ha; and energy = 27,737 GJ/ha), which, compared to the two previous scenarios, represent an increase in 27 and 25% in volume, 217 and 184% in biomass, 199 and 164% in carbon, and 200 and 188% in energy, respectively. Yet, trees at harvest age are distributed by smaller range of diameter classes (**Figure 1**) and present, on average, a lower diameter value in Scenario 3 than in Scenario 1 (28.8 and 38.5 cm, respectively), which is understandable since in these trees, the height growth was promoted, in detriment of diameter growth, to reduce the influence of the crown.

The forest management model of Scenario 3 is based on high stand densities followed by several heavy thinning (with 35–40% of the number of trees per ha removed in each intervention), which, in principle, reduces the amount of juvenile wood on the stem [26, 27]. It is expected that the wood from these trees presents better quality than the models with lower stand density. The forest management practices that can be used to regulate spacing between trees and act as a tool for wood quality improving are well documented in Ref. [26].

More recently, several studies with Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* L.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) concluded that higher stand density associated with high thinning intensity led to a significant change of the main wood properties for conifer species. The highest mean basic density, modulus of elasticity (MOE), and modulus of rupture (MOR) were obtained in the sites with the highest stand density followed by heavy thinning [28–32].

So, in addition to the higher productivity provided by Scenario 3, probably the trees will also have better wood quality.

In a minor extent, this feature also applies to Scenario 2. The average size of the trees, at harvest age, is lower in Scenario 2 (28.9 cm) than in Scenario 1 (38.5 cm). This difference is also expected as the average density of Scenario 2 along the rotation is higher than the one observed with Scenario 1, which is an attribute of Oliveira et al.'s [11] model to minimize the development of understory vegetation.

Regarding Scenario 4, whose management model is equal to Scenario 3 up to 12 years and the main difference is the reduction of the rotation from 45 to 20 years, it does not seem very advantageous if the objective is the production of larger pieces

of wood (and of higher economic value), even considering that in the 45-year period, it would be possible to have two rotations with Scenario 4. The anticipation of the final cut to 20 years is strongly penalized by the significant reduction in the total volume of wood obtained (741 and 218 m³/ha in Scenarios 3 and 4, respectively) aggravated by the fact that this wood comes from trees with a small diameter (only 11.1 cm) and low-economic value. However, if the main objective is the production of small material, for example, to supply the biomass units, pulp, panels, or pilings, Scenario 4 will be the most recommendable. After 20 years, this Scenario 4 provides slightly lower values of biomass (1318 t/ha), carbon (490 t/ha), and energy (20,705 GJ/ha) than the 45 years of Scenario 3 (1745 t/ha, 659 t/ha, and 27,737 GJ/ha, respectively), but after two rotations with Scenario 4, the yield will be much higher than with the other scenarios.

In this regard, it is important to emphasize that the production of pellets in Portugal is the second most important use for the pinewood in the country, whose annual production capacity is approximately 1.4 million tons [2, 3]. According to Nunes and Freitas' [33] ranking results, the Portuguese pellet productivity capacity per forest area in 2012 surpassed the total production of Central and South America, Africa, and Oceania and matched that of the entire Asian region, with Portugal representing the country with most installed capacity of pellet production plants per forest area in the world.

Thus, both Models 3 and 4 can be extremely useful to guarantee the supply of these pellet production units while alleviating the pressure to the forest roundwood in Portugal [34].

Finally, it is also worth mentioning the enormous amount of energy provided by Scenario 3 (27,737 GJ/ha) and Scenario 4 (20,705 GJ/ha), that is, the energy equivalent to 662 and 495 toe (tons of oil equivalent), respectively. Thus, if these models are adopted, they will allow approximately 890 t of biomass to be collected per hectare at the age of 8 from the natural regeneration of maritime pine, thus contributing to an additional yield from forest stands. However, in addition to this economic benefit resulting from the anticipation of an income (which definitely compensates for the costs with the operation), there is also the fact that this biomass contains around 13,500 GJ of energy equivalent to 323 toe, allowing part of the country's energy needs to be met through a natural, renewable source, with a neutral balance in CO₂ emissions, thus helping to comply with the commitments of Quito signed in 1998 and the Paris Agreement in 2015.

Concerning silviculture issues, managing stands in high values of density is demanding, namely to assure stability to the wind effects. A disadvantage that could be imputed to Scenarios 3 and 4 is the vulnerability to wind damages as it is expected that trees growing in dense stands present high values of height/diameter ratios, which usually denote lower stability to the wind effects [4]. As stated by Schaedel et al. [35], the long-term effect of lower stand density is to produce trees of larger size and greater stability while not sacrificing the stand yield. In stands growing at high densities, losses can occur by windthrow. In dense stands, the resistance to the wind is mostly provided by the group (block effect) [4]. Performing a thinning will interfere in the stability provided by the group. Special care with thinning practices should, therefore, be taken into account with Scenarios 3 and 4, if the stands are located in areas exposed to wind. In that situation, Scenario 4 might be a better option instead of Scenario 3 as it presents a minor interference in the stability to avoid windthrow (only two thinning, both made at early stages in contrast to the five interventions scheduled in Scenario 3) and a shorter rotation (a reduced risky period). In areas prone to forest fire, due to its minor rotation length, Scenario 4 might also be considered an option of lower risk.

5. Conclusion

The results of this study corroborate the influence of management in the total yield of maritime pine species and provide new insights into the management of naturally regenerated dense stands.

The results obtained through simulation with the new design of silvicultural guidelines (Scenario 3), of managing a high dense stand, since the early stages of development proved that a considerable potential of yield, in terms of biomass and energy, can be achieved in those early interventions. Further, this new design provides multiple uses of the removed trees, as noticed by the range of mean diameter values of the removed material, and material of good quality.

Although the prescriptions of density regulation set in Scenario 3 should be interpreted as a possible recommendation, a new path on the management of maritime pine is already identified.

If the objective of forest stands is the production of small woody material, such as biomass for energy purposes, pulp, panels, or pilings, Scenario 4 will be the most recommendable since it provides the highest productivity per unit of time.

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Conflict of interest

No potential conflict of interest was reported by the authors.

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