

Sustainable Forest Management in Radiata Pine Plantations: A Case Study in Sardinia (Italy) [†]

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Abstract: The study deals with the sustainability of management in radiata pine (*Pinus radiata* D. Don.) plantations of an area of Sardinia (Italy). Focusing on management strategies that foster a continuous forest cover and processes of natural regeneration, the aim was to evaluate the benefits arising from different types of plantation management, balancing social, cultural, environmental and economic aspects. Systematic and selective thinning, as well as regeneration cutting, were carried out in test areas of 45-year-old plantations, and outcomes were compared by considering current forest dynamism, natural regeneration and technical and economic aspects. From an economic perspective, silvicultural management strategies were always positive, with differences depending on the type of intervention. The regeneration cutting, with the expected natural regeneration of radiata pine in the following years, ensures the best economic outcomes, allows for a continuous forest cover and favors the replacement of even-aged plantations, boosting biodiversity in forest stands (structure, species). Climate change, increasing pests and wildfires represent the biggest threats to the sustainability of plantations in Mediterranean areas, and sensitivity is higher in even-aged, homogeneous, monospecific tree stands. In the context of the study, turning forest plantations into more resilient and stable ecosystems can be effectively achieved by means of continuous-cover forest management strategies.

Keywords: forest thinning; forest utilization; continuous cover forest; natural regeneration; radiata pine; plantation forests; forest sustainability

1. Introduction

Radiata pine (*Pinus radiata* D. Don) plantations were established since the end of the seventies of the last century, mainly in the southern part of Italy, where Mediterranean climate conditions, with a mild winter and a relatively cool and humid summer, are the most suitable for the species [1]. At the beginning of the eighties of the last century, the surface of pine plantations in Italy was about 25,000 hectares, almost half of which in Sardinia [2]. In recent decades the surface has been reduced as a result of exploitation without replacement of old plantations and wildfires.

In Sardinia, radiata pine was planted as a fast-growing species in areas that generally had little forest cover and low interest for grazing. Intensive interventions using mechanical equipment for site preparation did not spare the native vegetation, which was present at that time mostly as shrubs or small trees [3]. Even today, the main problem is

to limit the degradation of the soil by maintaining the forest cover as much as possible and carrying out fire control. Plantations were originally set up with an important public financial contribution, which favored the local socio-economic development all over with a large-scale employment of people.

The main objective of these plantations was to supply raw material to the pulp and paper industry that was developing in Sardinia on the central-eastern coast of Arbatax (Tortolì, NU). The failure of this industrial project at the end of the last century made the destination of plantation timber more uncertain, and today, the planted radiata pines having reached economic maturity, the future of plantations is an issue of public debate. The Regional Forest Agency for Land and Environment of Sardinia (FoReSTAS) is looking to the future, associating traditional forest interventions with innovative actions carried out in the managed public forests that can offer significant and innovative options to reduce forest degradation and increase its most significant multiple functions, essential for underpinning sustainable development [4].

More generally, wider social benefits should be considered for forest plantations. Direct and indirect benefits are provided by ecosystem services which originate from the presence of forest plantations in an area. The development of local timber transforming economies, as well as environmental aspects (landscape, biodiversity, carbon sequestration, water quality, soil erosion) represent new challenges for forest managers. On the other hand, plantations of non-autochthonous forest species can have negative impacts, such as an unnatural forest dynamism, and have gained a negative public perception when these have been ignored. Foresters are faced today with the need to ensure wider benefits from forest plantations, through minimizing negative effects, and to manage plantations in order to balance social, cultural, environmental and economic values [5].

The main issue behind this study is the sustainability of management in radiata pine plantations of an area in inland Sardinia, by integrating biological and ecological aspects with socio-economic constraints and opportunities. Managing radiata pine plantations as complex ecosystems might be infeasible if they are considered as artificial and relatively simplified forest stands. From another perspective, though, they contain large, long-lived trees that interact in different ways with the environment and can respond to disturbances as resilient ecosystems which maintain stability over time [6].

A key management goal for silvicultural decisions in Mediterranean conditions is to maintain a continuous forest cover over the soil surface in order to limit soil erosion and impoverishment [7]. As harvesting operations in intensive plantations and the removal of mature trees cause dramatic changes to soil conditions and microclimate, the study deals with management practices (thinning and regeneration cuttings) that reduce damage to the soil by fostering a continuous cover forestry (CCF) approach. The CCF silvicultural system refuses clearfelling by accepting cost penalties and provides more diverse forests for multi-purpose benefits [8]. Although little experience on this issue has been gained for Mediterranean parts of Italy, the potential benefits involved in the application of continuous cover management principles in the conditions of the plantation site are discussed.

2. Materials and Methods

The study was carried out in the forest complex of Monte Idòlo (Arzana municipality, province of Nuoro) at the localities “Su Pradu” and “Sa es corriasa”, on nearly flat plains (9% slope), at an altitude of 880 m a.s.l., with soils of medium depth and characterized by diffuse stoniness. Radiata pine was planted 40 years earlier with an original distance between plants of 2 × 2 or 2 × 3 m, which changed to 5 × 5 or 6 × 5 m after thinning was carried out at the beginning of this century.

As the forest cover is characterized by the dominance of the non-autochthonous radiata pine, and only a sparse layer of other tree species in the undergrowth, the overall management aim was to enhance the regeneration processes with silvicultural

interventions and the evaluation of environmental and socio-economic aspects. In order to analyze different management options, in the study we compared two thinning types with a regeneration system based on CCF principles. Three test areas (Figure 1), each about 3000 m², were established in order to compare:

- systematic thinning, with the felling of one row out of three in the plantation, which corresponds to a reduction of about 30% of the total woody mass of the stand, without considering single trees' features, aiming to create sufficient light conditions for the start of a natural regeneration process;
- selection thinning, with a similar total mass reduction, focusing on the best plants of the stand and subsequent felling competitive codominant and suppressed trees, as in the case of crown thinning, this way also encouraging the natural regeneration process by improving light conditions without interrupting the forest cover;
- regeneration felling, by choosing groups of plants around a gap to be felled, following only silvicultural criteria, in order to support the natural regeneration process to spread centrifugally around the gap under conditions of full light or slight shade on the margins of tree crowns; in this case, the felling started from small groups of existing regeneration of radiata pine, which in the area presents a remarkable capacity of regrowth from seeds dispersed by the wind on the bare soil; as the felling reduced the mass of the stand by about 40%, particular attention was paid in order to maintain soil protection by the continuity of the forest cover.

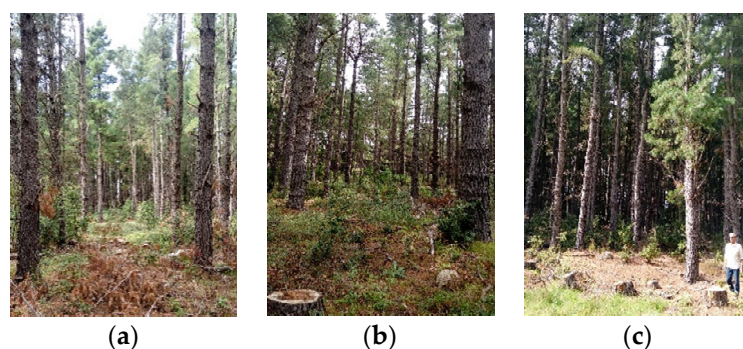


Figure 1. Stand management interventions considered in the study: (a) Systematic thinning; (b) Selective thinning; (c) Regeneration felling.

Forest extraction conditions of the area were favorable for adopting advanced forest mechanization vehicles. In fact, during the late summer season of 2019, cuttings were carried out by a crew of four skilled workers using chainsaws (Stihl 260), the extraction of whole trees was done by tractor and winch (Same 70 CV, winch DH70), and finally, on the landing, cross-cutting was performed by a processor (Kamo Euromach 125R of 125 kW, with Konrad Woody 50 processor head).

An analysis of forest regeneration and vegetation of the undergrowth was performed using the point-centered quarter (PCQ) method before tree felling, in the test areas and in an area for reference, with measurements on four transects, each comprising five plots. The PCQ method is widely used to study forest structure and the importance (density) of species in the forest stand [9].

Data on tree felling, processing and extraction operations were analyzed using ANCOVA (analysis of covariance) and simple, multiple and qualitative variable linear regression provided by the software package R.

3. Results

The undergrowth of radiata pine plantations analyzed through the PCQ method (Table 1) shows the highest absolute density for holm oak (*Quercus ilex*) with 3351 plantlets/ha above the regeneration layer, followed by pine (1139 plantlets/ha) and cherry

tree (*Prunus avium*, 536 plantlets/ha). With a relative density of 62.5 and a relative frequency of 50, the holm oak occurs homogeneously in sample points and number of quarters. With lower absolute densities, the other species show a similar distribution. In the shrub layer absolute densities are lower, with *Prunus spinosa* having the maximum absolute density of 203 plantlets/ha.

Table 1. Most important tree (T) and shrub (S) species in the regeneration layer.

Species	Rel. Density	Rel. Cover	Abs. Density
<i>Quercus ilex</i> (T)	62.50	50.00	3351.94
<i>Pinus radiata</i> (T)	21.25	25.00	1139.66
<i>Prunus avium</i> (T)	10.0	15.00	536.31
<i>Prunus spinosa</i> (S)	45.0	32.61	203.44

Holm oak is a shade-tolerant species that can regenerate under the canopy of pines and occurs as “advance regeneration” in the area (Figure 2a), whereas the light demanding radiata pine requires very light canopies or small gaps for the establishment of seedlings (Figure 2b).



Figure 2. Natural regeneration in the managed areas: (a) Holm oak advance regeneration under pine canopy; (b) Regeneration felling creates an open area to achieve adequate growth for the light-demanding radiata pine.

The impact of harvesting operations on the number of plants and distributions between diameter classes varies between management types (Figure 3).

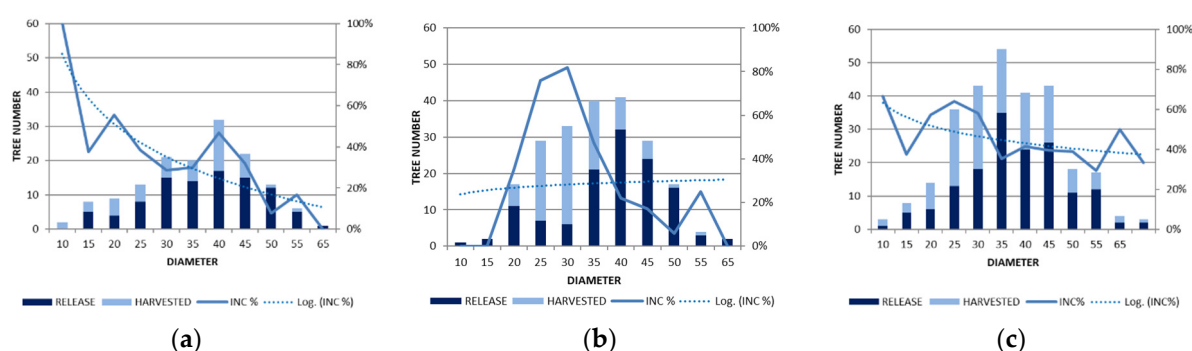


Figure 3. Impact of harvesting operations on forest stand as number of released and harvested trees, and relative incidence (INC %, Log): (a) Systematic thinning; (b) Selective thinning; (c) Regeneration felling.

The analysis of harvesting operations showed that the felling time was significantly related to the weight of trees (ANCOVA $F(1, 257) = 450.32, p < 0.000$), and the interaction between weight and type of management was significant, $F(2, 257) = 8.76, p < 0.000$. Higher productivity is shown in systematic thinning, followed by regeneration felling and therefore selection thinning, although this difference is only evident for plants weighting more than 1.2 tons (Figure 4).

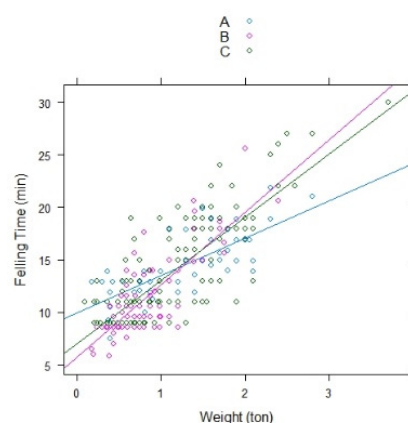


Figure 4. Felling time in relation to the weight of trees in systematic (A), selective thinning (B) and regeneration felling (C).

While time for the wood processing was linked to weight, $F(1, 261) = 386$, $p < 0.000$, with an R^2 of 0.595, the extraction time was significantly dependent on distance, $F(4, 161) = 103.4$, $p < 0.000$, R^2 of 0.714, whereas loading and management system did not affect the process.

Apart from the products of lower value (firewood and wood chips), the assortment with higher value is saw timber (about 70 €/t), which is required by the packaging industry (pallets). A multiple linear regression was calculated to predict the saw timber volume based on the diameter and height of trees, stem shape, tree class and management type. A significant equation was found, $F(8, 261) = 1179$, $p < 0.000$, with an R^2 of 0.972. The saw timber predicted volume increases with tree diameter (0.156 m³ for each cm) and tree class (0.157 m³ for dominant position) but decreases with tree height (−0.267 m³ for each m), where the management system and presence of forks in the trunk had no significant influence. Overall, the maximum economic benefit is obtained from regeneration felling (11,000 €/ha), while thinning operations reduce the revenues by about 36% for the systematic and 61% for the selection type (Table 2). In any case, management intervention has a positive outcome in economic terms.

Table 2. Summary data of the three management interventions: harvested timber (Yield), intervention costs (Costs), assortment value (Value), economic balance (Revenue: Value-Costs).

Management	Yield t/ha	Costs €/ha	Value €/ha	Revenue €/ha
Systematic thinning	220.6	7131	14,118	6987
Selective thinning	235.2	10,039	14,282	4243
Regeneration felling	405.7	14,809	25,809	11,000

4. Discussion

The undergrowth of the radiata pine plantations examined was dominated—in the regeneration layer—by holm oak (*Quercus ilex*), which represents the principal component of the forest vegetation in the area, often mixed with other tree species such as *Quercus pubescens*, *Phillyrea latifolia* and *Arbutus unedo*. The cherry tree (*Prunus avium*) is a species of the first phase of the ecological succession, which occurs scattered in the woods on soil with more moisture. Given the uniform distribution of holm oak regeneration highlighted by the PCQ analysis, forest management might address silvicultural operations aiming at preserving existing natural regeneration processes and improving the establishment of this species, until now still insufficient to guarantee the growth of a closed forest cover for the near future. Thinning, as well as the regeneration felling which was performed during

the study, will improve microclimatic and soil requirements for holm oak seedlings by assuring the conditions of light and soil moisture for the shade tolerant *Quercus ilex*.

On the other hand, holm oak and the other autochthonous tree species grow more slowly than radiata pine, which in that area was observed to regenerate naturally with vigor after the disturbance created by forest operations. Taking into consideration as a final goal the long-term recovery of the autochthonous forest vegetation (a mixed holm oak forest with some other tree species—e.g., *Quercus pubescens* and Mediterranean sclerophyllous elements—all over in the low productivity areas [4], one or more cycles of naturally regenerated radiata pine formations (mixed with the upcoming regeneration of the abovementioned native species) seem an affordable and sustainable goal for forest management, as a new radiata pine plantation would be infeasible due to the changed environmental, economic and social conditions.

For a cautious forest management approach, selective crown thinning focuses on the quality of the remaining trees but increases the forest operation costs. In this study, in comparison with systematic thinning, the costs were about 30% higher, whereas the value of timber assortments was almost identical (about 14,000 €/ha). In the long term, the selective crown thinning seeks to favor the crown development of seed trees, while ensuring that site conditions remain optimal for natural regeneration.

On the contrary, starting from pre-existent natural regeneration in groups or gaps, regeneration felling focuses on quickly improving the process of establishing a new generation of trees, taking advantage of the ability of radiata pine to regenerate naturally in the area. In this case, mainly due to the greater harvested wood mass, the value of timber is higher (about 23,000 €/ha), and consequently the economic gain (difference between the costs of forest operations and the value of timber) is higher. In any case, the three management options performed a positive economic gain, which accounts for the convenience of forest operations from an economic point of view.

The environmental advantages of the CCF approach in managing radiata pine plantations in Sardinia, besides the increased use of natural regeneration, which allows for the establishment of native tree species as discussed above, are the continuity of the forest cover, which leads to an increase in biodiversity, as well as a greater abundance of deadwood by releasing stumps and small branches after felling operations and a more cautious soil protection. This can be of crucial relevance in Mediterranean areas, if compared with the often-used clear-cutting management of radiata pine plantations.

From a social perspective, the implications related to this study deal with mitigating the problems related to the poor perception of clearfelling, which originated public debate in previous years in other harvested radiata pine plantation areas of Sardinia, as well as positive environmental benefits deriving from forest formations in the inner part of the island [10]. On the other hand, the local value chain starting from the wood produced in these plantations might have a positive impact on employment. There is also a rising recognition of the landscape and cultural values of conifer plantations in the area.

5. Conclusions

The sustainability concept is usually understood as meeting present needs without compromising the needs of future generations. For exploited ecosystems, such as forest plantations, the aim is to preserve ecosystem health and productivity, by considering ecological processes and functions, enhancing economic, social and environmental values [5,6]. In the observed case study of inner Sardinia, the high productivity of radiata pine and its natural regeneration ability, in comparison to native tree species which slowly appear in the undergrowth of the plantations, facilitate the prosecution as managed silvicultural systems with many economic, environmental and social benefits, which over time will be gradually replaced by native tree species.

Climate change, increasing pests and disturbances (wildfires) represent the biggest threats to the sustainability of these plantations, whereas sensibility is higher in even-aged, homogeneous, monospecific tree stands. Continuous cover forest management

strategies, by contrasting these limiting factors, can help in the long term help to change the forest structure and species composition of these plantations to resilient and more stable ecosystems.

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