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Review article

Silvicultural considerations for the production of poles in *Pinus radiata* D. Don plantations in Chile

Consideraciones silvícolas para la producción de postes en plantaciones de *Pinus radiata* D. Don en Chile

Considerações silvícolas para a produção de postes nas plantações de Pinus radiata D. no Chile

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ABSTRACT

The production of poles in Chile is done by choosing trees specially selected for that purpose, however, the forestry that is massively applied is oriented to the simultaneous production of pruned, sawn and pulpable logs. Silviculture for the specific production of poles in Chile is a technically complex issue, not addressed to date, whose description and analysis is what this review attempts to outline. The technical requirements of poles in terms of size, stem shape, knots, nodal thickening, straightness, spiral grain and resistance were analysed. These requirements were related to the variables site, stand density, genotype, pruning, thinning and harvest age. From the analysis of the variables it was concluded that a high-density forestry is required with multinodal plants in sites of regular too bad quality, but that generates high density wood with a low pruning and a selection thinning

Keywords: stem shape; knots; wood strength; silviculture.

RESUMEN

La producción de postes en Chile se realiza escogiendo árboles especialmente seleccionados para ese objetivo, sin embargo, la silvicultura que masivamente se aplica está orientada a la producción simultánea de rollizos podados, aserrable y pulpables. La silvicultura para la producción específica de postes en Chile es un tema complejo técnicamente, no abordado hasta la fecha, cuya descripción y análisis es lo que se intenta esbozar en esta revisión. Para ello, se analizaron los requerimientos técnicos de los postes en cuanto a tamaño, forma fustal, nudos, engrosamiento nodal, rectitud, grano en espiral y resistencia, los que se relacionaron con las variables sitio, densidad del rodal, genotipo, poda, raleo y edad de cosecha. Del análisis de las variables se concluyó que se requiere una silvicultura de alta densidad con plantas multinodales en sitios de regular a mala calidad, pero que genere madera de alta densidad con una poda baja y un raleo de selección.

Palabras clave: forma fustal; nudos; resistencia de la madera, silvicultura.

RESUMO

A produção de postes no Chile é feita escolhendo árvores especialmente selecionadas para o efeito; no entanto, a silvicultura aplicada maciçamente é orientada para a produção simultânea de toros podados, serrados e em pasta. A silvicultura para a produção específica de postes no Chile é uma questão tecnicamente complexa, não abordada até à data, cuja descrição e análise é o que esta revisão tenta delinear. Para tal, foram analisados os requisitos técnicos dos postes em termos de dimensão, forma do eixo, nós, espessamento nodal, retilinidade, grão em espiral e resistência, que estavam relacionados com as variáveis do local, densidade do povoamento, genótipo, poda, desbaste e idade de colheita. Da análise das variáveis, concluiu-se que a silvicultura de alta densidade com plantas multinacionais é necessária em locais de qualidade regular a fraca, mas que gera madeira de alta densidade com baixa poda e desbaste de seleção.

Palavras-chave: Forma do caule; nós; Resistência da madeira; Silvicultura.

INTRODUCTION

The growing global awareness of the impact of climate change and the depredation of natural resources, occurred in the last century, on the future development of humanity opens up a challenge to the forestry sector to generate new wood products to replace building materials, given energy and CO_2 balance is significantly higher (Leskinen *et al.*, 2018; Bösch *et al.,* 2019; Tettey *et al.,* 2019).

Sathre and O'Connor (2010) determined that for every ton of dry wood that is replaced by non-wood products, an additional 3,9 equivalent tons of CO_2 are emitted. These authors point out that the use of wood is an important element in a long-term strategy for climate change mitigation. The poles that were originally made of wood and that were mostly replaced by reinforced concrete and metal, in light of the new environmental paradigm, have a potential market both national and international, (Francis and Norton, 2006; Lu and Hanandeh, 2016).

The production of poles and wooden crossties in Chile in 2015 reached 290 000 m^3 with a share of 1 % of total consumption in pieces using almost exclusively *Pinus radiata* D. Don (Pinus insigne). The production was concentrated in the regions of O'Higgins (14,2 %), Maule (42,3 %) and Biobío (21,1 %), using mainly plants with a capacity of more than 1000 m^3 of production per year. That year, 97 plants participated, four of them concentrating 82 % of the total production. The market for these products was mainly domestic with only 36,470 m^3 exported. The main uses were for agriculture reaching 63,2 % and the rest, construction and electric pole. The products marketed are characterized by having a wide variety of sizes in length, diameter and processing, which can be cylindrical or natural with or without preservatives.

The main characteristics of the poles are related to the load bearing properties, the size of the logs and their sanitary condition. The major constraints are related to product size, presence of knots and nodal thickening, straightness, spiral grain, tapering and product maturity.

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Some standards that regulate the quality of poles are the NCh 2122 for Chile, the NZS 3605 for construction, the NZS 3605 and NZS 3607 for fencing poles in New Zealand (Carpenter, 1995). While in United States, the norm is ANSI 05.1 (Wang and Bodig, 1990), which is the oldest and most widely recognized norm for the classification of poles (Cerda and Wolfe, 2003). Although there is no single norm, all use visual grades of logs that are directly linked to the physical and mechanical properties of the wood.

Pinus radiata is classified as a perishable species. Under natural conditions and exposed to the soil it is highly susceptible to fungal attack. The heartwood, which is the most resistant section to biodeterioration, starts to form only after 12 to 14 years and also deteriorates within the first five years (Chee *et al*., 1998), so it must be impregnated as a basic condition for use as poles. The preservatives used for the impregnation of the logs of *P. radiata* in Chile are controlled under the NCh819 standard and the certifying company is Fundación Chile.

The supply of logs for this industry in Chile is mainly based on the purchase of raw materials, with only 11 % being self-sufficient (INFOR, 2016, p. 2006-2015). The supply of forest for the pole and wooden crossties industry comes from forests managed for the production of unwindable, sawn and pulpable logs. If, on the other hand, we consider the deficit in wood supply caused by the mega fire that occurred in 2017 in the main raw material supply zone and the fact that in Chile no new plantations or industrial investments are envisaged since the country has reached a plateau in terms of the productive capacity of its forests or plantations, hence it can be concluded that this industry should have its own plantations for its supply.

The technical management requirements for the production of poles of high size and quality standards may in some cases be incompatible with intensive management schemes (Cown and Hutchison, 1983). Until, 2019 the only study related to that was done by Manley and Calderon (1982) with some basic ideas for the production of poles in *P. radiata* in New Zealand. This paper analyse the main factors affecting the quality of logs for pole production: density, site, genetics, pruning and thinning of *P. radiata* plantations.

Therefore, here it is presented a review of the technical determinants to be considered for the production of poles. This review describes the main characteristics of the poles and how they are affected by the site and forestry, in order to make a specific proposal for their production.

DEVELOPMENT

Roll size and taper

The most restrictive condition for producing large diameter (30 cm) and long (12 m) poles is to achieve large size trees. If, for example, it is considered as a reference value to produce a pole 11,5 meters long, with a minimum of 17,5 cm at the lower end and a maximum of 30 cm at the upper end, the stand to be harvested should have a geometric mean diameter of 27,1 cm and an average height of 29,8 m. These values are reached from the age of 26 years in unmanaged plantations, and at 27 years in stands managed for pulp, in the dry interior of the Region of Libertador Bernardo O'Higgins and the coastal zone of the Region of Maule. For the same stand but with 6 m long pole, with a minimum diameter of 16 cm and a maximum diameter of 22 cm, the ages drop to 18 years in both cases.

The size of the tree is achieved by managing the planting density, applying intermediate thinning and regulating the harvest age. For the same zone, the management schemes used in Chile for the production of pruned, sawn and pulpable trees consider two or three prunings, a thinning to waste and a commercial thinning, with rotations that vary between 16 and 23 years for pulp and 20 to 27 years for intensive management, planting densities of 1 250 trees per hectare and final harvest between 700 and 400 trees per hectare, respectively (Fundación Chile, 2005).

For pole production in New Zealand, Manley and Calderón (1982) tentatively proposed a plantation of 2 500 trees per hectare, with two thinning to be carried out, the first when the stand reaches 5 to 6 m dominant height leaving 1 700 trees per hectare and the second when the stand reaches 13 to 14 m dominant height leaving 1 000 trees per hectare, with a final harvest at 30 years. However, these authors point out the difficulty in estimating pole production, expecting to produce at least 500 units per hectare with a percentage of the total standing volume of 40-50 %. The proposed stand density is based on having a balance between natural mortality and branch size, as proposed by Grossman and Potter-Witter (1991) in plantations of *Pinus resinosa* Ald. in the United States of America. On the other hand, Manley and Calderón (1982) point out that very low densities (600 trees per hectare) at harvest age can mean to obtain undesirably large sizes for poles.

Density management also has an impact on shaft shape or taper and consequently on pole production. If the poles are calibrated in diameter, *i.e*. perfectly cylindrical, it is advisable to maintain a high density in the plantation by taking advantage of the trees in the intermediate canopy whose trunk shape are less conical than the dominant ones, and it will also help to avoid wood losses in the process of calibrating the roll (Larson 1963; Corvalán and Bown, 2013; Jacobs *et al.,* 2020).

Likewise, thinning should preferably be oriented to favour the growth of trees with straightness and good cylindrical shape. Therefore, Manley and Calderón (1982) suggest that should be done a high thinning. Management through control of planting density, thinning, pruning, fertilization or genetic origin (Jacobs *et al.,* 2020) has a direct effect on the shape of the tree and thus on the production of poles. Thinning accentuates the conicity of the trunk by allowing more light to enter at the position of the lower branches, accelerating their physiological activity.

Cown (1974) points out that thinning has a greater effect on diametric growth at the base of the tree and decreases in height. Thinning tends to concentrate growth at the base of the trunk immediately after it is carried out and then redistributes it throughout the entire pole profile during rotation. Its effect is evident in up to five years. It also known, at long term, lower positions in the trunk have less conicity than at higher ones. Pruning generates the opposite effect to thinning since the removal of the branches at the base of the tree decreases the wood aggregation in this position and increases at the base of the crown which is photosynthetically active, making the trunk more cylindrical (Lewis *et al*., 1993; Hevia *et al*., 2016).

Management regimes rarely use only pruning or thinning, it is usual to perform them together in temporal sequence (Fundación Chile, 2005), for that reason there is scarce information to quantify the change into a pole stage form separately. Nevertheless, Fernandez *et al*., (2017) reported a greater conicity in pruned and thinned stands than in those without intervention.

Bi and Turner (1983) report on the effect of fertilization applied between four and five years on the change in pole shape in a natural regeneration of phosphorus-deficient *P. radiata* in Australia. After 30 years, the authors found an increase in the cylindrical shape factor from 0,33 to 0,40 when fertilizing with 100 kg ha^{-1} of phosphorus. The shape factor is explained by the increase in the pole diameter in the lower third of the tree, similar effect to that of pruning.

Similar results were reported, in the short term, by Gordon and Graham (1986) in New Zealand, who found an improvement in the pole form, although not significant, when phosphorus was applied. Corvalán and Bown (2013) also report a positive change in the pole form in application of sanitary sludge to juvenile *P. radiata* plantations on the coast of the sixth region of Chile.

The site has direct impact on tree size (Kimberley *et al*., 2005; Ojeda *et al.,* 2018; Resende *et al*., 2018). In good sites the stands reach greater height and diameter, are more cylindrical, straighter, with smaller branch size and nodal thickening than in sites of poorer quality (Maclaren, 1993). The sites of lower quality would produce less amount of poles than better sites, however, and due to the longer cultivation time required to reach the desired pole size, the density of its peripheral wood is also higher. For this reason, Manley and Calderon (1982) propose to use soils where the site index is less than 27 m.

Genotype selection also controls the straightness and growth rate, being the multinodal trees straighter and having a higher initial growth rate than the uninodal type, which would compensate at older ages their growth rates (Lavery, 1986). But, if the production of long poles is projected, this factor would not seem to be relevant.

Nodal knots and thickening

The knots constitute a major defect that reduces the strength of the wood due to the change in the orientation of the grain and also affects the area in the vicinity of the knot (Lavery, 1986). In a test on samples of 25-year-old dried *P. radiata* wood pieces from Kaingaroa Forest, in New Zealand, Cown *et al*., (1996) proved that there is a very significant correlation between the maximum tensile strength of sawn wood with the knot area ratio and with the diameter of the largest branch of the piece, with values of -0.67 and -0.56, respectively.

In another strength study with 52 poles of *P. radiata* with 2,44 m length and diameters of 20 to 30 cm at greenwood stage in the North Island of New Zealand, Walford and Chapman (2010) proved that the physical-mechanical characteristics decreased linearly with increasing knot diameter ratio but with a non-significant loss of strength and stiffness, which its attributed to the fact that the knot location did not always coincide with the pole break point. In contrast, in another trial carried out in Chile on 12 m long poles in greenwood stage Cerda and Wolfe (2003), concluded that the greatest number of fractures are caused by the presence of knots or whorls. In New Zealand, a maximum knot size of 10 % of the circumference is accepted for posts and 20 % for poles (Carpenter, 1995), while in Chile, for poles less than 13,5 m long the maximum admissible diameter should not exceed 51 and 102 mm for the lower and upper half of the pole, respectively (Campos, 1987).

The maximum size of the branches or knots is strongly influenced by the available growth space (Sutton, 1968; West and Smith, 2020). Lavery, (1986) using information from a paper by Pederick and Abbott, in Melbourne, points out that there is a positive linear relationship between the average final branch size at the basal portion of the piece, the diameter at breast height (DAP) and the growth space.

Similar results are reported by Wang *et al.,* (2018) in *Betula alnoides* plantations in southern China. This relationship manifests one of the greatest complexities of management: if the size of the tree is to be increased, more growth space must be given, which will lead to an increase in the size of the branches. Silvicultural regimes seek a point of equilibrium where a decrease in stand density does not compromise excessive branch development and with it, wood quality.

Siemon *et al.,* (1976) evaluate the effect of various thinning intensities on branch size, finding that this can increase significantly, especially in the upper half of the crown (between 50 and 80 % of the total height) by increasing the proportion of branches whose size is greater than 3 cm and also doubling the section of the middle area of the branches, a situation which ceases to have an effect in positions above 80 % of the total height. Branch size is also affected by pruning as reported by Lewis *et al*., (1993) who, citing a paper by Jacobs conducted in 1938, point out that the area at the base of the first branches located immediately above each pruned shoot grows additionally by up to 74 % and 66 % in the first and second year after pruning, respectively.

Fernández *et al.,* (2017) point out that the size of the branches in the upper position of the trunk presents a larger diameter than in managed stands than in those not managed in *P. radiata* plantations in 18-year-old stands. In *Eucalyptus nitens* Deane et Maiden, Pinkard (2002) found that a 20 % pruning increases branch growth rates between 48 % and 68 %, nine months after pruning. Low pruning is a direct way to control branch size and nodal thickening in that position of the stem from which the posts will be obtained, however, plantation density seems to be a more efficient way of control (Manley and Calderon, 1982). Fenton y Familton (1961) point out that nodal thickening in *P. radiata* can reach five cm in diameter, which is completely out of the norm for classification as a pole.

Another important factor that determines the size of the branches is their position at the height of the trunk. The final size of a branch depends on its vitality, age and historical growth rate. The largest branches are those that develop and expand when the tree is growing at its highest rate and are preferably located in the intermediate height position (Siemon *et al*., 1976). In pruned, thinned and fertilized stands, Corvalán and Bown (2013) found an increase in the branch rate (understood as the average diameter of the four branches with the largest diameter in each quadrant of logs of 2,44 m) in the treatments of application of composted sludge loads with respect to the control.

Given that the branching characteristics of the species are determined in the initial growth stage, *i.e.* up to 8 years of age, and that the poles, due to their size, make up a large proportion of the final length of the tree, it is advisable to select the trees destined for final cut very early (Lavery, 1986). *P. radiata* presents two alternatives when selecting branching habits: trees with multiple annual whorls (multinodal) or one whorl per year (uninodal) (Lavery, 1986). The characteristics that are positively related to branch frequency are the number of cones produced, the angle of the branches, the pole straightness and the regularity of the pole tapering, and the characteristics that are negatively related are the length of the internodes and the diameter of the branches. These characteristics can somehow be controlled or accentuated by the growth space.

Certainly, the multinodal type seems to be more propitious for the production of poles due to its straightness and smaller branch size, which can be as small as 1 cm in diameter (Carson and Inglis, 1988), coinciding with what was pointed out by Kininmonth and Whiteside (1991). Genetic selection can be fundamental in achieving the maximum branch size in the portion of the tree from which long logs are obtained (12 m) according to the required standards. An additional problem that limits pole production is nodal thickening (Fenton and Familton, 1961); Lewis *et al.,* (1993) which occurs especially in uninodal trees where the vigorous whorl branches growing at the same height of the tree can cause large diameter differences between the whorl and internodes (Maclaren, 1993). Larger spacing also produces larger nodal thickenings (Carter *et al.,* 1986). For example, in New Zealand this value should not exceed 20 mm (Carpenter, 1995).

Moreover, Maclaren (1993), points out that trees growing at high site indexes have smaller branches size and nodal thickening than at lower sites indexes. This description induces to think that good sites are adequate for the pole production, however, the arguments pointed out by Manley and Calderon (1982) regarding the characteristics of wood density result in a contrary proposal.

Straightness

The straightness is conditioned by genetic factors (Jayawickrama and Low, 1999). The heritability of this traits assessed between 5 and 9 years varies between 0,17 and 0,28 and is less than the height and diameter (Wu *et al.,* 2008). Ståhl *et al.,* (1990) and Malinauskas (1999) point out that Pinus sylvestris L. trees growing in small spaces have straighter shafts than those growing with greater spacing. Similar results are reported by Carter *et al.,* (1986) in Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco, and Erasmus *et al.,* (2018) in Pinus patula. The positive effect of high density on straightness can be adversely affected by factors such as snow and wind (Malinauskas, 1999).

Spiral grain

The spiral grain, understood as the angle at which the tracheids deviate longitudinally with respect to the main axis of the trunk, is a characteristic that makes the wood reduce its strength, especially the static bending, which can be 50 % less than a straight grain wood when it reaches a 9,5° turn (Lavery, 1986; Cown *et al.*, 1991). Another important effect is the condition of turning the wood when it shrinks by drying. This characteristic is present in juvenile wood, reaching its maximum deviation according to Bamber and Burley (1983) between the third and fifth year of formation and according to Cown *et al.*, (1991) in the tenth year, with an average value of between 4° and 5° and with extremes of -7° to +18°, after which it persistently declines until the age of 15 years (Cown *et al.,* 1991). The direction of rotation is usually against the clock and seems to be related to the phyllotaxis of the fustal needles and the flow of auxins (Lavery, 1986). Spiral grain is increasing in height and is present in all juvenile wood along the trunk and is highly heritable (Cown *et al.,* 1991; Moore *et al.,* 2015).

This characteristic of the spiral grain accentuates the need to use mature logs, in which the peripheral wood is sufficiently old to present a minimum deviation of the grain considered to be of the order of 2°. To this end, it is very important that the poles come from the basal section of the tree, so that the spiral grain in its smaller section is of minimum impact, since the logs obtained from higher heights will be more prone to rotation given their younger age and the natural tendency to increase the angle of inclination of the tracheids that the species presents in that position of the trunk.

Wood maturity

The most important characteristic of a pole is its ability to withstand loads (Cown and Hutchinson, 1983; Campos, 1987). Static bending strength is linearly related to the density of the wood and the wood in turn is related to the modulus of elasticity (MOE) and modulus of rupture (MOR) (Walford and Chapman, 2010). In practical terms, the way to ensure that a post has the right density to support the loads is measured through the number of growth rings in the smaller diameter section of the poles (Cown and Hutchison, 1983; Campos, 1987).

Cown and Hutchinson (1983) show that both modulus of rupture and modulus of elasticity are linearly related to the average density of the wood measured in the outer 20 % of the radius of both ends of the post, with determination coefficients close to 0.8. The percentage of late wood correlates positively with wood density, modulus of elasticity and modulus of rupture, and negatively with ring width. Wood density varies radially in the trunk as a function of age (Cown and Hutchison, 1983; Cown and McConchie, 1983).

Also the density of the wood is always greater in the peripheral zone and base of the tree (Cown, 1974; Harris and Cown, 1991). For that reason, the best location to get a pole with maximum strength is at the base of the trees. New Zealand, for example, requires its fence poles to be a minimum of 0,7 years/cm in diameter (Carpenter, 1995), while the ANSI Standard for poles prescribes a minimum of 2 years/cm but with a proportion of 40-60 % late wood in the peripheral 5 cm (Cerda and Wolfe, 2003), both measured at the lower end of the pole. Wood density can be controlled by increasing the age of rotation (Cown, 1974); Harris and Cown, (1991) and also with site and soil selection.

Cown and Hutchinson (1983) show how in New Zealand it is possible to predict both the mean basic wood density of 20 % of the pole's peripheral radius and its modulus of elasticity and splitting at ages between 10 and 30 years for different sites of wood density classes and thus to evaluate its suitability for use. Besides, these authors also shown how high density sites can achieve the required densities to qualify for poles earlier than medium and low density class sites. The results of the study indicate that according to NZS 3603 only high density wood sites can reach the required modulus of elasticity of 9,1 GPa from 25 years onwards as it requires basic wood density of more than 450 kg m^{-3} . This study agrees with Manley and Calderon's (1982) suggestion that it is preferable to choose site indices below 27 m.

Another factor that determines the density of the wood is the growth space with which it is weakly and negatively related. Watt and Trincado (2017) point out that as the height/diameter ratio of the tree increases, the modulus of elasticity increases significantly, a situation that is favoured by greater stand density. Thinning in plantations may temporarily produce less dense woods, but at the end of the rotation, its effect is minimal.

Cown (1974), points out as an example that a thinned stand of 25 years with an average diameter of 40 cm has a density between 8 % and 10 % less than a stand of the same size at 35 years. This same author points out that high thinning intensities can decrease the density of the peripheral wood up to 18 m in height (Cown, 1974).

Pruning also has a positive effect by increasing resistance in the pruned area, however, at the end of the rotation the variation is minimal. Fertilization also has the effect of decreasing the density of the wood by up to 10 % equivalent to the density

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of non-nutrient deficient sites (Cown, 1974). The effects of forestry are reflected in changes in stem density that are greater at the base of the trees and decrease towards the apex. An important factor in controlling density is the genetic origin. Cown (1974) points out that density can be increased by up to 15 % following the selection of phenotypes proposed by Shelbourne, given the high degree of heritability of this trait.

Summary and analysis of the effect of forestry actions on critical variables in pole production

The Table 1 presents the fundamental effects that silvicultural actions have on the most restrictive characteristics of the posts (Table 1).

Table 1. - Interactions between silvicultural variables and limiting factors for pole production

Silvicultural control variable	Pole production limiting factor						
	Size of the roll	Ahusa-miento	Size of knots	Nodal thickening	Fustal rectitude	Spiral grain	Wood maturity
Growth area	+	+	+	+	-	s/i	-
Site Index	+	-	-	-	+	s/i	-
Number of whorls per year	+	-	-	+	+	s/i	s/i
Thinning	+	+	+	s/i	s/i	s/i	-
Pruning	s/i	-	+	s/i	s/i	s/i	s/i
Fertilization	+	-	+	s/i	s/i	s/i	-

+: positive relationships, -: negative relationships, s/i: undocumented relationships

The selection of multinodal trees seems to be a key factor in the production of poles since they have a higher initial growth rate, greater straightness, less conicity, smaller branch size and nodal thickening than uninodal trees.

The use of reduced growth space also allows control of stem taper, branch size, nodal thickening and peripheral wood density, even if this means extending the age of rotation. The lower site indexes lengthen the rotation generating a /wood with a higher peripheral density, thus improving the physical-mechanical properties for the production of poles. Thinning fundamentally contributes to the initial selection of individuals for the final harvest. The impact on the size of the branches, nodal thickening, tapering, straightness and density of the wood is of temporary effect, which at the age of rotation have already been standardized.

Pruning have a sense only for health and accessibility reasons, since like thinning, it has no major long-term impact.

Fertilization does not make much sense either, with the exception of sites with nutritional deficiencies.

The effect of twisting the logs can be only avoided by lengthening the rotation, essentially preventing the poles from containing only juvenile wood.

CONCLUSIONS

In summary, the key factors for the production of poles in P. radiata are: relatively dense plantations with multinodal plants, in regular to poor quality sites with high density wood production, accompanied by low accessibility pruning and selection thinning. Management schemes for pole production should be formulated and evaluated with specific simulation studies.

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