Chapter

Thinning: An Overview

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Abstract

Thinning is one of the primordial silvicultural practices. It has been analysed by its methods and intensities, associated to the tree selection criteria. Yet, while some methods are of generalised use, others were developed for specific purposes. The goal of this review is to compile the existing information regarding tree selection, thinning methods and intensity as well as their effects on trees and stands. The effects of thinning indicate a reduction of density and a trend towards an increase of growth rates at tree level for a short time after thinning. Biomass and volume show similar or smaller values when compared to unthinned stands. Mortality and growth stagnation, especially in stands with low stability or vigour, can also occur. The modifications in stand structure can enhance its role as an adaptive measure.

Keywords: method, intensity, stand structure, growth, adaptive measure

1. Introduction

Stand and forest management encompasses a set of silvicultural practices which are designed according to its goals. Among these, thinning is of primordial importance as it influences stand structure, tree and stand growth, products, yields and diversity.

In time, the trees of a stand occupy gradually the available growing space, developing simultaneously facilitation and competitive interactions [1]. The balance between these two interactions is dynamic, but competition increases with the decrease of the growing space. The result is that individuals with competitive advantages reallocate the growing space formerly occupied by other individuals with less competitive advantages and suppress them. This originates from the development of a social structure which, when growing space is fully occupied, derives in the death of the suppressed individuals, that is, self-thinning [2].

Thinning implies always the removal of trees with the main goal of allocating the growing space to those better suited to the desired productions and yields [2–6]. The removal of trees can have both positive and negative effects. The positive, are related to the reduction of competition, anticipation of volume losses due to self-thinning, increase of diameter growth rate, increase of timber value and revenue and reduction of the damages due to the abiotic and biotic disturbances. The negative, are associated with the reduction of total volume, risk of mortality or growth stagnation, cost of the operation, damages in the remaining trees and risk of damages by abiotic and biotic agents [2, 6].

In literature, thinning has been analysed according to its method and intensity as well as with the tree selection criteria. Yet, while some methods are of generalised use, others were developed for specific purposes. The main goal of this review is to compile the existing information regarding tree selection, thinning methods and intensity as well as their effects on trees and stands. The chapter is organised in four sections. Section 2 describes and characterises tree selection criteria. Section 3 analyses the thinning methods and intensity. Section 4 analyses the effects of thinning on stand structure, growth, products and as an adaptive measure.

2. Tree selection

Tree selection plays one of the key roles in thinning, as one of its main objectives is the reallocation of growing space to a set of trees in the stand. Care has to be taken so that the trees maintained in the stand are able to use the growing space made available [2, 6, 7]. Thus, it has to be thought at two complementary levels: (i) at tree level, reallocating the growing space to the trees kept so that they reach the desired growth rates, yields and product quality and (ii) at stand level, optimising yield for the desired production cycle, which is also related to density, spatial arrangement and site quality. These levels derive from two tree development traits, namely, the intrinsic and the external. The former is mainly driven by genetics, preponderant when trees grow isolated. In the latter, the growing space availability determines trees development [1, 2, 8]. These complementary objectives enable balancing interactions to achieve growing space use optimization and improve the overall stand quality and yield.

The need of selecting trees enhanced the development of tools to evaluate growing stock, stability, potential photosynthetic ability and growth rate [1–3, 6, 9]. One of the mostly used is the tree classification system. Their main advantages are that tree and stand description, evaluation and monitoring (both spatial and temporal) can be carried out with a set of qualitative criteria, needless of forest inventories. The stand evaluation is quick with low costs and helps to implement silvicultural practices. The disadvantages are related to their development or adaptation to stand structure and management goals, to not enabling a quantitative evaluation and to the need of skilled practitioners [2, 6–8, 10].

Due to the variety of stand structures and management goals, many tree classification systems were developed. They evolved in time, increasing in complexity, as more criteria were included to increase accuracy and precision [7, 8, 11]. Typically, tree classification systems are grouped in two broad classes according to the stand structure and production goals. One is directed towards pure even-aged stands with one main production (timber), for example, of kraft [10], of 1902 [10], English [12], of Assmann [2], Belgian [3], of Meadows and Skojac [11]. The other is directed to pure or mixed uneven-aged systems with one main production or several ones, for example, of Assmann [2], of Florence [8], of IUFRO [7], of Meadows [13] and of Perkey classification [14].

The concept of future trees is related to tree characteristics, moment of selection, number of trees per unit area and their spatial arrangements.

The criteria associated with the future tree characteristics referred in independent studies (e.g. [3, 6, 7, 15–19]) are similar, and eight criteria can be pointed out: (i) vigour and good sanitary conditions, (ii) social position (dominant or codominant), (iii) suitability of the species mixture, (iv) vertical straight stem, (v) without stem deformation (forks) up to 6–8 m for timber and 2–4 m for bark and fruit production, (vi) wood without serious defects, (vii) final ramification, few small branches in the case of timber production and to be promoted to increase production in the case of bark and fruit and (viii) balanced crown. These criteria can be totally or partially used depending on the management and production goals.

The moment to designate the future trees is not consensual, however, some guidelines have been reported [3, 7, 17, 19]: (i) social position maintenance – young trees have higher probability of social regression than adult ones; (ii) species tolerance to shade – shade-tolerant trees are able to live suppressed and, after release, are able to ascend to dominant positions whether intolerant are not; (iii) low risk of sudden death or break and free of wounds – trees should be vigorous, stable, in good sanitary conditions and without injuries; (iv) stability – trees should be stable enough so that after release they are able to develop with low probability of falling down and (v) longevity – it should be ensured that they are able to reach the end of the production cycle. The selection should then be made as earlier as possible, as soon as the probability of changing social status is low. It can be done when trees reach 10–25 cm of diameter at breast height [3, 17], or 20 m of dominant height [17] or 10–14 m of stem height [17]. When it is convenient to designate future trees very early in time, a preselection of the future trees is recommended, followed by their selection later, for example, after 30–40 years [3, 4, 7].

The number of trees per unit area is determined by the release from the competition of the future trees during the entire production cycle, to optimise their development. A density between 80 and 250 trees ha^{-1} is suggested [4, 7]. The better the site quality and the shorter the production cycle, the higher their number. The larger the crowns and the lower the shade tolerance, the lower their number [7].

The spatial arrangement of the future trees should be uniform to enable a more efficient and complete use of the growing space while maintaining the growth rate at highest desired levels, which corresponds to a mean spacing of ≈7–12 m, depending on the species ecological and cultural characteristics [4, 7].

3. Thinning method and intensity

Thinning method or type can be defined by the classes and social position of the removed trees, although other parameters such as stem and crown characteristics are also important [2–6]. Nine methods have been identified, namely from below, from above, selective or Schädelin, of dominants, mechanical, free, compensation, crown release and variable density thinning.

Thinning from the below main goal is to favour the best trees of the upper layer, of better dimensions and crowns. The removal of the individuals starts with the dead, dying and dominated, and only if necessary the codominant and dominant individuals (mainly, individuals of bad characteristics) are removed. It has low effect in the subsequent growth of the remaining stand. Thus, it only anticipates the normal pattern of tree senescence and dead in an unthinned stand. It is suited for sites where water is a limiting factor [2–6]. The best results are attained with intolerant species, where the stems of the inferior layers do not have or only have a limited reaction to release [6].

Thinning from the above main goal is to favour the best trees of the upper layer until the end of rotation. The trees to be removed are predominantly in the upper layer and in direct competition with the best trees. The inferior layers are maintained with the objectives of enhancing natural pruning, soil protection, reducing spontaneous vegetation development, increasing resistance to wind and maintaining or enhancing wildlife habitat. However, the tree removal in the inferior layers can be considered for aesthetical reasons or to reduce the risk of fire, creating vertical discontinuity [2–6]. It is better suited for shade or semi-shade-tolerant species, in pure and mixed stands, especially when quality trees are found in an adequate number in the superior layers. It is not suited for shade-intolerant species, especially in the later stages of development [6].

Selective or *Schädelin thinning's* main assumption is the selection of the future trees. They can be selected in all social classes, according to a set of criteria (cf. Section 2). The thinning is focused on the release of the future trees, with the removal of all competitors and the maintenance of trees that can be useful or do not interfere with them. Also, the future trees should have, as much as possible, a uniform spacing. Its selection is not static in time, especially in young development stages. Thus, before each thinning they have to be checked and, if necessary, reselected [7, 20, 21]. The main goal of this thinning is the optimization of the production in value rather than in volume, favouring at the same time the mechanical and ecological stability [7, 20].

Thinning of dominants is focused on the upper layers. The dominant and the codominant trees are removed, including the more promising and those of the intermediate and inferior layers are favoured. It is suited for a reduced set of objectives, and care should be taken so that it does not derive in the harvest of the best trees. Three approaches can be considered, as a function of the objectives and number interventions [6]:

i. Thinning of dominants *with temporary character*: The goal is to improve the overall stand, with the promotion of lower layers that have individuals with good characteristics, both in growth and quality. It is suited for stands where the irregular or low density has originated dominants of bad quality; for shade-tolerant species, as the stems in the lower layers maintain their vigour and ability to react to release and it is less suited for intolerant species, yet it can be used in young stands where trees have not lost their vigour. It should be done as earlier as possible and should be replaced by the thinning from below as soon as the trees reach the superior layer.

ii. Thinning of dominants *with permanent character*: The goal is the production of small- and medium-dimension timber. The objective is to promote canopy gaps that enhance regeneration with the largest possible number of individuals with the removal of dominant trees. When the stand is dense and uniform, this method is replaced by the thinning from below. The rotation length is considerably shortened.

iii. Thinning of dominants *combined with thinning from below*: The goal is forming a superior layer with codominant individuals. It minimises the negative effects of the thinning of dominants, especially in very dense unthinned stands. Its main disadvantage is the tendency to increase the losses due to biotic and abiotic disturbances.

Mechanical or *geometric thinning* is associated to large spacing silviculture with selected material, in which the removal of a tree is more related with its location than with its position, because the goal is to maintain a regular cover. It is advantageous in young, very dense unthinned stands. Two subtypes can be identified: *spacing*, where the trees at a certain distance of the selected tree are removed; and *row* or *strip*, where the individuals of one or several lines are removed [6].

Free thinning goal is the selection of a set of trees which are maintained in free growth until the end of the rotation in order to produce high quantity of timber with high quality [22]. It is directed to oak species and rotations of less than 100 years. It begins with the selection of the future trees with a density of 60–80 trees ha^{-1}, uniformly spaced. It is followed by the removal of all the trees whose crown distance from a future tree is less than 25% of the mean crown width (assumption to be maintained throughout rotation, to keep future trees in free growth). As a secondary silvicultural practice, pruning is recommended up to a height of 6 m as well as removing the epicormic branches [22, 23]. It has also been used in mixtures of conifers and oaks, and oaks in pure or mixed stands with *Fraxinus excelsior*, *Acer pseudoplatanus* and *Prunus avium* [24].

Compensation thinning's (*éclairci de ratrapage*) aim is favouring the future trees that have sufficient stability and well-balanced crowns, being less important in their spatial distribution and their optimal distance. It is frequently linked with the goal of keeping stand stability and should have light intensity. It is preferred in stands without or with thinnings of low intensity in the past. In these cases, only the dominant stems are able to react to release, and thus codominant individuals should be preferably removed. It is especially suited for stands in steep slope areas where it is easy to overestimate distances due to crown overlapping and asymmetry [7].

Crown releasing thinning's (*éclairci misse en lumiére*) main goal is regulating future trees in old growth development stage. The trees' metabolism and growth, capacity of reaction to release and ability to redo their crowns are lower than in the mature ones. The social positions are nearly definite, and the probability of individuals of the inferior social classes to ascend to upper classes is low. Future trees are released from competition from those of the intermediate layers as the dominant competitors were removed in the former thinnings. The objective is to maintain or increase diameter growth, to allow the largest possible increase of productivity in value. The intensity should be light and periodicity should be long, according to the trees' growth rates [7].

Variable density thinning's goal is to promote variability and heterogeneity, both spatial (horizontal and vertical) and structural [25–28], as well as stimulate late-successional forest structures, reduce stand density, alter species composition [25, 26, 29] and be a restauration tool [27, 30, 31]. It assumes the unevenly removal of trees, creating gradients of density in the stand. This is implemented with the creation of patches with variable spatial distribution, where canopy gaps and patches of different densities coexist [26, 27, 32]. The proportion of each patch type is also variable according to the intended complexity of stand structure, the existing stand structure, the species composition and spatial arrangement [31, 32]. Six protocols are referred, which due to their similarities were grouped in four types [32]:

i. *Randomised grid*: Stand area is divided in a grid with cells of equal area and the number of individuals to be maintained is randomly sorted. Two target densities can be chosen, low (≈185 trees ha^{-1}) and moderate (≈370 trees ha^{-1}).

ii. *Dx rule*: Selected trees define density depending on site variability and tree dimensions. The area of influence of each selected tree is defined by a circle proportional to the diameter at breast height by k-fold (e.g. k = 2). In this area, trees between a diameter range are removed, while those outside it are kept. The upper and lower thresholds can be defined per stand or per species. The areas outside the circles are not thinned.

iii. *Spacing thinning*: Stand area is divided in a square point grid (e.g. ≈5 × 5 or 6 × 6 m) as well as a buffer for each point (e.g. ≈1.2 m). For each buffer area, the best tree larger than a diameter threshold is selected and released from the competition.

iv. *Localised release*: Stand area is divided in a point square grid associated to a buffer (e.g. 7.6 m of radius). In each circular area, three trees are selected irrespective of their spatial arrangement with the same rules as the former type, while the areas outside the buffers are either thinned with about 3.6 m spacing in the row space outside the buffers or remain unthinned (e.g. third or fourth row).

Thinning *intensity* or *degree* is more frequently evaluated by the number of trees or basal area, as function of the amount of removed in relation of the total number of stems ($RN = \frac{Nrem}{Nt}$, where Nrem is the number of removed trees, and Nt is the total number of trees) or basal area ($RG = \frac{Grem}{Gt}$, where Grem is the basal area removed, and Gt is the total basal area). It is frequently grouped in three classes: light, moderate and heavy. The most consensual ranges for light intensity are ≤25% of the number of trees and <20% of the basal area, for moderate 50% of the number of trees and 20–35% of the basal area and for heavy >50% of the number of trees and >35% of the basal area [33, 34].

4. Thinning effects

The main goals of thinning are to improve residual trees' efficiency, encompassing to concentrate growth on a selected subset of trees, thus controlling density and reallocating the growing space and reducing competition among trees while promoting their growth [35–39]. It is also considered as a mean of capturing tree mortality, providing early financial return, increasing future merchantable volume and financial value of timber [39–41]. Moreover, density threshold (or thinning intensity) enables to keep volume growth [42], which depends too on the species, stand development stage and site [41, 43, 44]. The thinning effects will be discussed for density, stand structure, stability, mortality and growth stagnation, growth, wood, biomass and carbon stocks, soil and understorey and as an adaptive measure.

Regardless of the method and intensity of thinning, *density* decreases always. All thinning methods increase individual tree growth due to the increase in growing space and reduction of competition [45–48], especially in the long term [47]. The method affects differently tree interactions post thinning. In the thinning from below, the interactions in the upper layer are maintained [7, 49], while in the thinning from above, compensation and crown releasing thinning are reduced [7, 34, 50]. In the thinning of dominants, there is a change in the interactions in the intermediate layer, which is a consequence of the removal of the upper layer [6, 51, 52]. In the free and mechanical thinnings, the spatial pattern of interactions is kept [6, 22, 23]. In the Schädelin and variable density thinnings, future trees are released from competition, resulting in the alteration of the spatial patterns of interaction, both horizontal and vertical [7, 32].

In general, the heavier the thinning intensity, the higher the decrease of density and the lower the competition. This derives in different growth reactions post thinning, which is also related to stand development stage and site quality, with growth rates increasing with thinning intensity and site quality and decreasing from initial to old growth development stages [41, 43, 50, 53].

Stand structure is affected by thinning, producing more or less accentuated changes depending on its method and intensity. This changes with the increase of light, water and nutrients levels (e.g. [54, 55]). These alterations can be observed in the diameter and height distributions, canopy stratification and spatial arrangements of trees. Thinning from below and of dominants narrow the range of diameter and height distributions and decrease canopy stratification due to the preferential removal of trees with smaller and larger dimensions, respectively [52]. Thinning from above and of Schädelin keep the range of diameter and height distributions and maintain or increase canopy stratification [20, 39, 52, 56, 57]. Compensation and crown releasing, free and mechanical thinnings tend to keep diameter and height distribution ranges and canopy stratification [6, 7, 23]. Variable density thinning increases diameter and height distribution ranges and maintains or increases canopy stratification [29, 58–60]. The tree spatial arrangements after thinning depend on those prior to thinning. A regular spacing was reported for thinnings from below, while from above and of dominants have been referred as a trend towards cluster one at low and intermediate distances [52]. Schädelin thinning tends to derive in a uniform or cluster distribution when future trees are at uniform distances or in clusters [20].

Stand stability depends on individual tree morphology and their spatial arrangement. It is frequently evaluated by diameter at breast height, total height, *hd* ratio (defined as quotient between total height and diameter at breast height, with both variables in the same units), stem taper, crown dimensions, crown eccentricity and crown inclination as well as root architecture [61–63]. For the same diameter at breast height, the taller the total height, the higher the *hd* ratio and the lower the stability. The increase of stability can be achieved with thinning, as it promotes diameter growth, the *hd* ratio reduction and stem taper increase [21, 61, 63]. The crown dimensions (width and length), eccentricity and inclination depend on stand structure and species traits, which are determined primordially by the amount of light. The higher the light level and the wider the spacing, the higher crown volume, and the higher the shade tolerance, the higher the crown dimensions. The constellation of neighbours reducing or promoting irregular available aerial space can promote the development of eccentric crowns and stem inclination and thus reducing stability [64, 65]. Stability is attained more efficiently with thinnings at younger ages as it enables a more favourable above- and below-ground morphology [21, 66]. Also, heavy thinnings promote tree morphologies that are more stable than moderate or light ones [21, 41, 66]. Thinnings from below increase stability by the removal of trees with the less suited morphologies (e.g. higher *hd* ratio), and increase with the increase of intensity due to the reduction of *hd* ratio and increase of stem taper [37, 67, 68] and crown length and crown ratio (the coefficient between crown length and total height) [69, 70]. Thinnings from above and of dominants removing trees from the upper layer may decrease stability, especially when associated to trees with high *hd* ratio and due to unbalance of aerial/root systems, eccentric crowns and the swaying of trees [35, 52, 71]. Schädelin, variable density and free thinning maintain or improve stability of thinning as the trees more stable are selected [20, 22, 32, 72]. Compensation and crown release thinning maintain stability [7].

Mortality after thinning can be caused by increased tree swaying due to wind or snow [71, 73] or is associated to shallow root systems' water stress [35, 36]. In general, it is higher in the thinning from above and of dominants than from below [52] or Schädelin [72]. *Growth stagnation* [74] is linked to the reduction of growth increment [75, 76], sometimes associated to drought events [77–79].

The thinning effects on *growth* are related to a suite of factors such as method and intensity, age, species traits, density (cf. density section), stand structure (cf. stand structure section) and time after thinning.

In general, thinning increases growing space and favours certain classes of trees. This results in asymmetric competition [80, 81], that is, the share of resources used by larger trees is disproportionally larger than those used by smaller trees, resulting in the growth suppression of the latter [35, 80]. Thus the increase in growth at tree level is maintained or enhanced by the methods where release occurs in the upper layers and/or favours future trees (from above, Schädelin, free, compensation, crown release or variable density thinnings) [7, 20, 23, 30, 31, 39, 59, 60, 82, 83]. This is especially true if the thinning is carried out before canopy closure and crown recession [47]. It can be explained by two factors: the available growing space and the individual tree growth strategies. In closed canopy stands, the upper layers absorb most radiation, the taller trees cast shade on their smaller neighbours and tree swaying may derive branch abrasion [1]. These three factors promote height growth and constrain crown lateral development [84]. In fact, it has been reported that the dominant height increases with density for broadleaved species [41, 85], due its effects on epinastic control and specificities of stand development at early ages [41]. The inverse has been reported for the conifers [86, 87].

Thinning intensity influences directly density and thus the availability of growing space for individual stems, which in turn affects height, stem and crown growth [69, 88, 89]. Growth, at tree-level basis, increases with thinning intensity [37, 50, 71, 89, 90]. In general, smaller/medium and/or younger trees react faster and with higher growth rates than larger ones [50, 75, 91]. After moderate and heavy thinnings, especially those carried out early, dominant and codominant trees have higher radial growth than supressed ones [37, 38, 67, 71, 75]. Stand age and site also curtails the response to thinning, the younger the stand and the better site quality, the larger the diameter increments [37]. Moreover, dominant trees have higher diameter growth [37] and need less time to react to release [91]. This is especially true with mature trees that have reached their maximum growth potential [35, 71]. However, a positive trend in above-ground biomass has been reported for large trees [92–94]. This trend seems to be linked with shade tolerance. Shade-intolerant species increase growth with light increase, though reaching maximum annual growth at younger ages conversely to shade-tolerant species [35, 77]. Also, according to Bose et al. [35], thinning intensity plays a less important role in growth increase after thinning in very shade-tolerant species than in shade-intolerant ones as the former are not able to use the increased growing space after thinning (especially light) efficiently.

Differences in tree reaction to thinning with age also depend on the stand history. While in unthinned stands, recovery decreased with stand age, it did not decrease in thinned stands [95], at least partially explained, by the larger crowns in thinned stands that enable a faster recovery of growth [95, 96].

After thinning, the trees increase their growth, frequently 1–3 years after thinning [50, 82] due to the availability of growing space. The growth increase derives in the increase of crown volume (width and length), crown cover [90, 97] and foliar mass enhancing photosynthetic capacity, as the lower parts of the crowns receive more light than unthinned stands [98]. As trees occupy gradually the available growing space, the growth rate decreases [35, 36, 99] after reaching the maximum (about 3 years after thinning), attaining 7–8 years after thinning, growth levels similar to the unthinned stands [50]. Primicia et al. [99] reported that magnitude and duration of thinning effects on growth (stem and crown diameter) as well as on mortality seem to be more related to thinning intensity than with thinning method.

Wood quantity and *quality* can be improved by thinning. In general, quantity per tree increases with thinning intensity [100], though it depends also on the species and their ecological and cultural traits. Light thinnings favour more regular growth rings, especially interesting for timber, though with overall smaller diameter growth, while heavy thinnings promote larger annual growth rings [77, 101]. The counterpart of thinning is the development of large branches that reduce the wood quality. Consequently, a compromise has to be equated between low and high densities as function of the species and its traits (e.g. epinastic control and natural pruning ability), associated frequently to future tree selection, pruning and early silvicultural operations [21, 37, 38, 83], especially in what regards wolf trees, which should be removed as early as possible [102].

In general, thinning reduces *biomass* and *carbon storage* when compared with unthinned stands, the decrease is higher in thinning from above and of dominants [39, 103] than from below [104, 105]. Yet, the effects of thinning are dependent also on the individual tree development stage, their growth rates and density after thinning [106, 107]. In the short term, thinning of young trees results in a reduction of above-ground carbon even if there is an increase of the individual tree's growth rate, because they are not able to use all the growing space available, that is, they do not fully occupy the site [104, 108]. In general, increasing thinning intensities result in decreasing standing and deadwood biomass and literfall [109, 110]. At stand level, it seems that biomass and carbon storage is the result of the interaction between the density and size of the overstorey trees. Though with an inverse relationship, they balance each other, resulting in a rather constant above-ground carbon stock, regardless of whether stands are thinned or not [39, 41], especially with early thinning from below [41].

Soil and *understory* vegetations are affected by thinning. If biomass residues are kept in the stand, their decomposition incorporates carbon in the soil. Thinning increasing decomposition rates decreases the soil carbon stocks. In the 0–10 cm of the soil layer, carbon stock is higher than in the 10–20 cm layer [39, 40], due to higher decomposition rates [111]. Yet, with time and tree growth, soil carbon stocks tend to be similar in thinned and unthinned stands [112]. Zhang et al. [39] reported that soil carbon stocks prior and 5 years after thinning were similar. Thinnings originate higher light levels in the lower storeys, which can result in higher transpiration and water loss by evaporation (e.g. [54, 55]) and increase of the understorey vegetation, the higher the thinning intensity [39]. This is particularly negative if it is composed mainly by shrub vegetation [39]. Yet, heavy thinnings favour pasture production, a suitable option for agroforestry systems [90, 113].

Thinnings are considered primordial adaptive measures as they can reduce vulnerability to climate change, fires, droughts and increase diversity.

Thinning can reduce vulnerability to climate change [95] as it controls stand density [41]. It can improve tree and stand growth by releasing growing space (e.g. [41, 77, 114]), including increasing water availability and their use efficiency [77, 101], thus mitigating the effects of the droughts (i.e. water deficits) [77, 95, 114, 115].

Fire prevention is enhanced by thinnings (including also pruning) as they reduce the quantity and horizontal and vertical continuity of fuel, [116] enabling stands to withstand surface fires [117] and increase the canopy seed bank storage [118].

Thinning intensity has a primordial effect on the magnitude and duration of the drought effects on trees and stands. The higher the proportion of crown cover removed, the longer the effects of thinning, that is, more water reaches the soil, enabling drought effects' mitigation [95, 101, 119]. Less-intensive thinnings reach pre-thinning transpiration levels in a few years, [55, 114] while in heavy ones they last longer [119], occasioning tree growth rates' increase [95, 101, 120]. Broadleaved species seem to have developed resistance mechanisms, mitigating diameter growth reduction [121]. This can be due to the deeper root systems [122] and spring radial growth (especially in the ring-porous species) is much larger than in the autumn one [123]. Conifers seem to have improved recovery and resilience mechanisms, probably due to more precipitation reaching the soil and transpiration reduction [95, 121]. Regardless of tree species, the stronger the drought severity, the longer the recovery period in diameter growth [95], which is probably related to the longer period needed to restore the soil water and to rebuild fine root system [124]. Thus, species with higher expansion rates, increase of leaf area (assimilation ability) and fine roots (water absorption ability), are expected to have more benefits from thinning [115, 125].

An increased diversity in stand structure, especially in pure even-aged stands, particularly in plantations, can be derived from thinning in tree' dimensions [126] and/or their variability [20, 39, 52, 57] as well as in species and their proportions [127] and produces greater trade-offs with other ecosystem services [128, 129]. This is especially valid with methods that promote variability, such as Schädelin or variable density thinnings.

5. Conclusion

Stand structure and production goals influence the thinning method and its intensity, which in turn affects stand structure and the quantity and quality of the products. Thus, it is of primordial importance the selection of the most suitable methods (that can be more than one during the production cycle) as well as their intensities (which can vary too along the production cycle) that have also to be suited to the products and services desired to the forest stand. Thinning is frequently linked to tree selection. Tree classification systems are quick, low-cost tools that enable thinning implementation and are also a monitoring tool that enables the evaluation of the dynamics of the forest stands.

All thinnings reduce density, however, their effects on density, stand structure, growth, soil, understorey vegetation and diversity depend on the method and intensity of thinning, stand development stage and site quality. The positive effects of thinning are the increase in growth and production, especially in value, and the reduction of the vulnerability of the forest systems to climate change, droughts and fire. The negative effects are related to the reaction of the trees to release, which can cause mortality, growth stagnation or no increase of the growth rates.

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