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REVIEW ARTICLE

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A review of thinning effects on Scots pine stands: From growth and yield to new challenges under global change

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Abstract

Aim of study: Thinning experiments in Scots pine (*Pinus sylvestris* L.) stands have been carried out for many years in different regions of its distribution. The aim of this paper is to gather knowledge regarding the effects of thinning on Scots pine stands, from the effects on growth and yield to the provision of ecosystem services in the context of climate change.

Area of study: The review covers studies from different regions of the distribution area of Scots pine

Material and methods: We reviewed the effect of thinning on four aspects: growth and yield, stability against snow and wind, response to drought, and ecosystem services.

Main results: Heavy thinning involves a loss in volume yield, although the magnitude depends on the region, site and stand age. Thinning generally does not affect dominant height while the positive effect on tree diameter depends on the thinning regime. The stability of the stand against snow and wind is lower after the first thinning and increases in the long term. The impact of extreme droughts on tree growth is lower in thinned stands, which is linked to a better capacity to recover after the drought. Thinning generally reduces the wood quality, litter mass, and stand structural diversity, while having neutral or positive effects on other ecosystem services, although these effects can vary depending on the thinning regime. However, scarce information is available for most of the ecosystem services.

Research highlights: Existing thinning experiments in Scots pine stands provided valuable information about thinning effects, but new experiments which cover a broad range of ecosystem services under different site conditions are still needed.

Additional keywords: *Pinus sylvestris*; thinning schedule; growth; stand stability; drought impacts; ecosystem services

Abbreviations used: d (diameter at breast height); h (height); NWFP (non-wood forest products); WUEi (intrinsic water use efficiency)

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Introduction

Growth reaction to thinning has long been a research topic of interest in forest science (Zeide, 2001), and the correct choice of thinning regime to apply in a forest stand is one of the most important decisions in silviculture. The effects of thinning on trees and stand development and therefore on its functions and production has been studied in a number of experiments comparing different thinning regimes to unthinned stands established since the end of the XIX and beginning of the XX Centuries. The first results of many thinning experiments were compiled for Central Europe (Wiedemann, 1943, 1951; Assmann, 1970) and subsequently added to with numerous studies for different forest tree species and regions (*e.g.* Curtis *et al*., 1997; Pretzsch, 2005).

Conventional thinning studies focused mainly on growth and yield, assuming wood to be the main forest product. They provided general information concerning tree and stand growth, total yield, mean tree and size distribution and some studies also included characteristics related to wood quality, such as the taper or crown features (see Pretzsch & Rais, 2016). However, the ecological effects of thinning have also been analyzed since these studies began, with aspects such as litterfall, nutrient cycle, understory vegetation, etc. being monitored in several thinning trials (*e.g.* Thomas *et al.*, 1999; Roig *et al.*, 2005; Jonard *et al.*, 2006).

Today, timber yield has lost importance in some forest areas and the provision of other ecosystem functions and services have gained prominence in forest decision making. In order to support multi-functionality in forest management, it is necessary to identify the effect of different silvicultural treatments on the provision of ecosystem services, including the effect of thinning. Furthermore, in the context of global change, it is vital to determine the way in which forest stands will develop under different silvicultural alternatives in order to guarantee their sustainability. Existing long term thinning experiments can provide information which could help to satisfy the current demand for knowledge about aspects such as carbon accounts (Ruiz-Peinado *et al.*, 2013; 2016) or climate change impacts (Sohn *et al.*, 2016b). However, other aspects, such as non-wood forest products, might require new long term monitoring to determine the effect of different thinning treatments.

Scots pine (*Pinus sylvestris* L.) is the most widely distributed conifer species in the world, with natural forests and plantations throughout Eurasia. It has great economic importance as a timber producing species, particularly in northern European countries. At the limit of its southwestern distribution, where this species finds its habitat in mountain areas, many Scots pine forests have been managed since the end of the 19th Century for multiple objectives (wood production, soil protection, water regulation, etc.) (Montero *et al.*, 2008). However, a shift towards multi-functional forest management has also occurred in many other regions since the 1990's (Mason & Alía, 2001). As a consequence of the importance of Scots pine, a large number of thinning experiments were established in the last century (*e.g.* Mäkinen & Isomäki, 2004a,b; Eriksson, 2006; Nickel *et al.*, 2007; del Río *et al.*, 2008; Nilsson *et al.*, 2010). Most of these experiments focused on growth and yield but findings were sometimes contradictory, probably due to the large distribution area of the species, with high geographic variability in its response to environmental conditions (Rehfeldt *et al.*, 2002), as well as to differences in the experimental design and analytical methods employed (Zeide, 2001).

In this study we reviewed existing knowledge about the effects of thinning on Scots pine stands, including the effects on stand growth and yield, size growth of a selected group of trees within the stand (*e.g.*, dominant trees, selection trees, future crop trees), stand stability, and the provision of ecosystem services. The main objectives of this review were i) to summarize the general results of thinning experiments for this species; ii) to gather knowledge from other types of study that provide valuable information with regard to designing thinning schedules according to current demands for forest management.

In this review we considered 'thinning' as intermediate cuttings performed during the stem exclusion stage, which eliminate some of the trees from the stand to provide more growing space for the remaining trees. Although the thinning method can vary between pre-commercial and commercial thinning in forest practice, we did not distinguish between these two since the merchantable character of the extracted wood also depends on external factors not controlled by silviculture. We also excluded cuttings performed during the regeneration period. In some cases, especially where information from thinning experiments is scarce or completely lacking, we also include some results from studies dealing with stand density, since these results might allow us to infer the thinning effect. As regards the thinning intensities, the thresholds which define light, moderate and heavy thinning vary among studies. The average ranges of basal area percentage removed in the thinning treatments are: light (<20%), moderate (20-35%) and heavy (>35%).

Thinning effect on growth and yield

The primary objective of thinning is to control the stand density by reducing competition among trees and concentrating growth in a smaller number of trees. Generally, in forest practice, the effect of thinning on the size of the mean tree or future crop trees is of more importance than its effect on stand growth and yield, particularly for species like Scots pine, the wood value of which varies greatly with stem size. However, it is also important to quantify the effects of thinning on stand growth and the trade-offs between tree size and stand yield.

Volume growth and total yield

Whether or not forest growth can be increased by removing some trees or to what extent volume growth is reduced by heavy thinning are questions that have been addressed by studies for many years (Zeide, 2001). These questions can be answered by testing Wiedemmann's hypothesis, which states that volume growth is constant among a wide range of stand densities, also expressed by Langsaester's curve or density growth relationship (Langsaester, 1941; Wiedemmann, 1951). This relationship varies among species, but also depends on stand age and site conditions (Assmann, 1970; Pretzsch, 2005), so it is necessary to quantify this variation for each forest species.

The application of thinning throughout the rotation in Scots pine stands reduces the cumulative or total volume, *i.e.* lower volume increment, although the magnitude of this decrease depends on the thinning regime. The loss in total volume depends mainly on the intensity of the regime, the volume increment decreasing with the thinning intensity. This total yield-thinning intensity pattern has been observed in Scots pine thinning experiments where the extraction method was from below (Montero *et al.*, 2001a; Mäkinen & Isomäki, 2004a; del Río *et al.*, 2008; Nilsson *et al.*, 2010), a common method for Scots pine since it is particularly suitable for this shade intolerant species. However, reductions in total volume were also found for other methods (Dittmar, 1991; Nilsson *et al.*, 2010), as can be seen in Fig. 1 (right) for crown thinning or thinning from above. When comparing different combinations of the number and weights of interventions, Nilson *et al.* (2010) found greater yield losses with few heavy thinning interventions rather than with frequent light thinning, highlighting the importance of the thinning intensity on stand volume growth.

According to these results, the pattern of Langsaester's curve for Scots pine follows an increasing pattern, without an optimum below the maximum density. This pattern was also found by Gizachew & Brunner (2011) through models based on the Norwegian National Forest Inventory. However, some studies have identified the existence of a maximum, Assmann's optimum basal area (Assmann, 1970, pp: 229-232), for light thinning at young stand ages (Chroust, 1979; Kramer & Röös, 1989), which indicates the importance of the timing of the first thinning. Accordingly, the critical basal area following Assmann's definition seems to be lower at younger ages (Erteld, 1960).

The findings concerning the possible effect of site conditions suggest that the thinning intensity-total yield pattern does not differ significantly among site fertilities for Scots pine (Mäkinen & Isomäki, 2004a; del Río *et al.*, 2008; Gizachew & Brunner, 2011). However, the differences among thinning intensities seem to be higher at richer sites (Mäkinen & Isomäki, 2004a). In Fig. 2 the volume increment variation with the relative basal area for the extreme site qualities used in del Río *et al.* (2008) are presented, although for a longer study period. Despite the lack of significance of site in their study, it is noteworthy that at the better site, the loss in volume growth is greater and that at the poorer site, the maximum volume growth was found for light thinning. Therefore, one might recommend that the basal area after thinning should be higher on fertile sites compared to less fertile sites (Nilsson *et al.*, 2010).

Regarding differences among regions, it seems that the volume losses with heavy thinning (more than 35% of total basal area removed) are higher in Northern and Central European (22-37%) than in SW-European Scots pine forests (19%), the losses being similar for

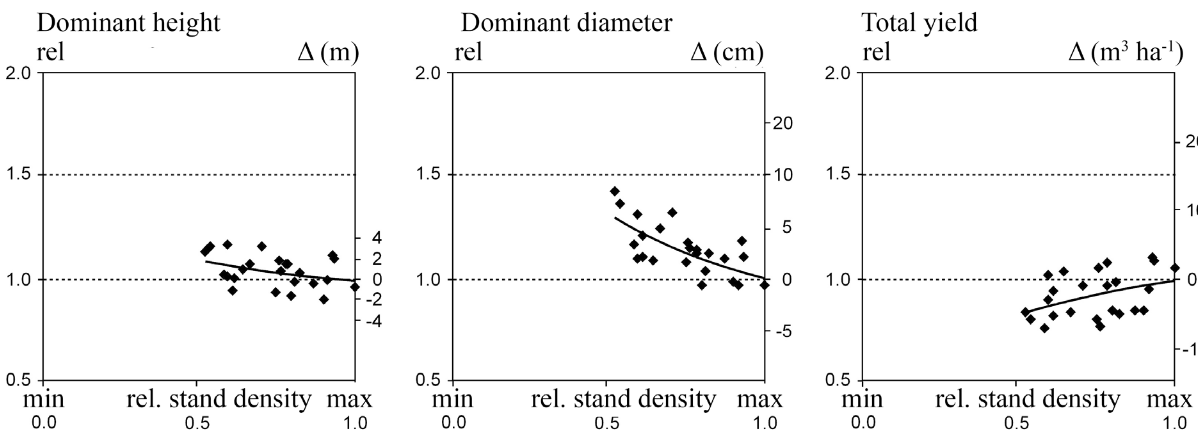

Figure 1. Reduction of stand density to 50 % below the maximum density (from relative density of 1.0 to 0.5) by spacing and thinning from above significantly increases the height and diameter of the 100 tallest trees per ha but reduces the total yield (from left to right) on the combined spacing and thinning experiments Weiden 611 in Scots pine till the stand age of 40 years (Nickel *et al.*, 2007). The x-axis displays the relative stand density (maximum=1.0 was 43 m^2/ha), the left y-axis shows the relative growth reactions (characteristics for fully stocked stands set to 1.0), and the right y-axis displays the absolute benefit and loss, respectively, in terms of height (m), diameter (cm) and total yield (m^3/ha) in thinned compared with unthinned stands.

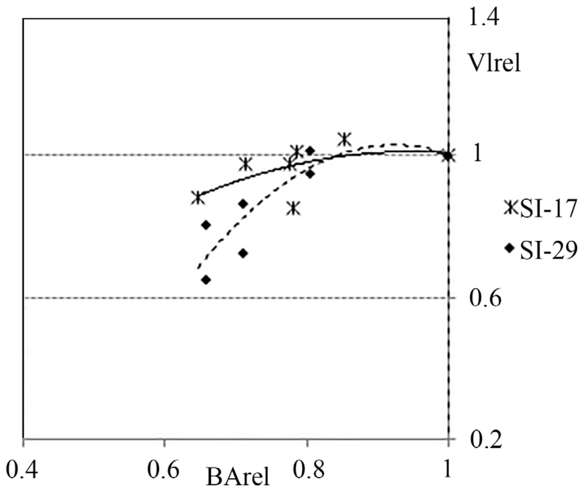

Figure 2. Pattern of volume growth reaction when reducing basal area by thinning in two experiments with contrasting site fertilities, poor site SI-17 (Covaleda) and rich site SI-29 (Ahedo Pinar) (del Río *et al*., 2008). A slight greater but non-significant volume growth (VIrel=1.05) is observed in lighter thinned than in unthinned stands for SI-17. SI, site index expressed as the dominant height at the age of 100 years. The x-axis displays the relative basal area in thinned compared with unthinned stands (maximum=1.0 correspond to the mean of unthinned plots by site fertility), and the y-axis shows the relative growth reactions in volume (1.0 corresponds to the mean of the unthinned plots by site fertility).

moderate (10-15%) and light (5-10%) thinning regimes (del Río *et al*., 2008). These regional differences might be due to the lower mean site quality in the latter region; to the longer growing season in southern areas, which might allow the remaining trees to recover occupancy of the growing space more rapidly; or to the possible influence of genetic variation among regions, although more studies are needed to elucidate the regional differences.

When thinning treatments were combined with fertilization, the periodic annual volume growth and stand volume were greater in unthinned fertilized plots, which showed a greater response to fertilization than thinned stands (Eriksson, 2006; Bergh *et al*., 2014). The aforementioned study suggested that repeated thinning may reduce stand leaf area to below the limit required to maintain maximum growth rates and that this reduction is not sufficiently compensated by fertilization.

The effect of thinning on basal area growth and total basal area generally follow a similar pattern to that on volume, although the differences among thinning intensities are less pronounced (del Río *et al*., 2008). Despite this, findings for basal area growth should not be extrapolated to the corresponding volume growth (Gizachew & Brunner, 2011). In some experiments, accelerated basal area growth was found at young stand ages (Erteld, 1960; Kramer & Jünemann, 1984; Montero *et al*., 2001a), in accordance with findings for volume growth.

Mean and top height

The tree selection criteria used in thinning has an important impact on the mean and dominant tree characteristics. In Scots pine thinning trials, thinning from below either has no effect on the dominant height of the stand (Valinger *et al*., 2000; Varmola *et al*., 2004; del Río *et al*., 2008) or only slightly reduces it in the case of heavy thinning intensities (Mäkinen & Isomäki, 2004a) since it is only the suppressed or intermediate trees that are removed. However, in a spacing-thinning experiment in Germany, where different initial stand densities were combined with thinning from above (Pretzsch, 2010, pp: 121-122), a higher top height was found at lower stand densities (Fig. 1, left). In plots with lowered density, the top height is one site class (up to 4 m) higher than in unthinned plots at an age of 40 years. Because of the shift in the calculation when eliminating the smaller trees, the superiority of the height of the tree with quadratic mean diameter of the thinned compared with the fully stocked plots is even higher (up to 6 m). The effects of the initial spacing on dominant height growth are still under debate, but significant height growth reductions as spacing decreases have been reported for a number of species (Burkhart & Tomé, 2012, pp: 166-167). Very high tree densities may drastically reduce space for tree growth, triggering a reduction in height, as found by Dippel (1982) and Spellmann & Nagel (1992) in the case of Scots pine. This kind of stagnation in top height development is typical in very dense plantations, where the homogeneity of age, space distribution and often genetics make social differentiation more difficult. However, in the abovementioned German experiment, height also differs between the control and the thinned plots for a given initial spacing. One hypothesis is that thinning significantly lowers drought stress and improves height growth at sites with low levels of precipitation, water storage capacity and mineral nutrient supply, as is the case at this site. The use of height as an indicator of stand productivity is therefore questionable, at least at dry sites; the effect of climate change might exacerbate this issue.

Tree diameter

Tree diameter growth response may depend mainly on the thinning schedule and the social status of the tree. For a given thinning intensity, the effect on the quadratic mean diameter and dominant diameter can vary significantly with the thinning method. Heavy thinning from below significantly increases the quadratic mean diameter of the stand, although part of this increase is due to the shift caused by removing smaller trees. The observed effect on the dominant diameter differs among studies for Scots pine; some reporting positive (Mäkinen & Isomäki, 2004a and references therein) and others, neutral effects (Chroust, 1979; Varmola *et al*., 2004; del Río *et al*. 2008). These differences might be due in part to differences in the timing of thinning treatments, the thinning intensities, and site conditions. Thinning through selection from above and based on the selection of future crop trees result in greater diameter increments for the selected trees (Kramer & Röös, 1989; Ditmar, 1991; Nickel *et al*., 2007), improving both stand stability and wood quality. However, the use of these thinning methods may not always be advantageous since they frequently involve heavy thinning intensities, with the associated yield loss (Franz, 1983; Küster *et al*., 2004). Moreover, in the case of the future crop tree approach, it is initially necessary to select a larger number than that expected to remain at the end of the rotation due to the occurrence of damage to trees and changes in tree social classes (Ditmar, 1991). The German combined spacing-thinning experiment provides insight into trade-offs between tree size and stand productivity using the thinning from above method (Fig. 1). The mean diameter can increase by up to 8 cm in the case of the 100 tallest trees (Fig. 1, centre) and 12 cm in the case of quadratic mean diameter. Fig. 1, (right) shows that the cost of obtaining these increases in mean tree size can be up to 80 m^3/ha in maximum total yield. This finding agrees with those reported by Franz (1983).

Other factors such as initial spacing, site characteristics and stand age may also affect the thinning response in terms of tree diameter growth. For Scots pine, a better diameter growth response to thinning has been reported at younger ages and at better sites (Franz, 1983; Mäkinen & Isomäki, 2004a). In the German combined spacing-thinning experiment, the benefit in terms of tree size along with the loss of total yield at the age of 40 years is caused, to a similar extent, by both the low initial density and the reduction in density through thinning (Küsters *et al*., 2004), highlighting the importance of initial spacing along with age at first thinning intervention for future stand development in this species. Regarding the combination of thinning and pruning, Moreno-Fernández *et al*. (2014) found no significant difference in tree diameter growth between thinned and thinned-pruned stands.

As regards the response to thinning depending on tree social status, some studies which have analyzed growth response to thinning according to tree size have found less difference between thinning intensities for larger trees and future crop trees in comparison to smaller trees (Kramer & Röös, 1989; Mäkinen & Isomäki, 2004b). However, Mehtätalo *et al*. (2014) found that tree size mainly affected response time, rather than maximum tree growth response, with much shorter response times in larger trees. Mäkinen & Isomäki (2004b) reported that in absolute terms, the effect of thinning decreased with decreasing relative size, although in relative terms, relative basal area growth in smaller trees was greater than in larger tress. Pukkala *et al*. (1998) reported that the best response to thinning occurs in trees of medium diameters.

Thinning effect on stand stability against snow and wind

Snow and especially storm damage appear to have increased in Europe during recent decades (Schelhaas *et al*., 2003; Gardiner *et al*., 2012). Climate change scenarios predict a higher frequency of heavy storms, so more widespread damage in forest systems can be expected if stands are not managed to reduce their vulnerability. Among European forest species, although *Picea abies* L. is the species most affected by snow damage, *P. sylvestris* is high on the list of species prone to such events (Rottmann, 1985; Valinger & Lundquist, 1992; Polley, 1995), with wind, as well as a combination of the two factors together being responsible for frequent damage in this species (Martín-Alcón *et al*., 2010; Schmidt *et al*., 2010; Zubizarreta-Gerendiain *et al*., 2012).

The main tree characteristics that determine the susceptibility of an individual tree to wind and snow damage are closely linked to the thinning regime previously applied in the stand. The most important tree attributes for stability are tree height, height/diameter ratio (h/d), and the length of the living crown, although other characteristics such as tree taper, tree diameter, crown eccentricity, stem inclination or root architecture can also affect tree stability (Petty & Worrell, 1981; Rottman, 1985; Lindström & Rune, 1999; Schmidt *et al*., 2010). Moreover, the relative importance of these tree attributes differs depending on whether the risk of damage is from wind or snow; tree height often being the variable most closely related to wind damage (Gardiner *et al*., 2010). In the case of Scots pine, different critical h/d values have been reported in the literature, ranging from 70 to 90, depending on the stand and site conditions (Rottmann, 1985; del Río *et al*., 1997).

Density is the stand variable which is most closely associated with stability, although its effect depends on other factors such as the type of abiotic factor or wind exposure. Generally, the higher the density the greater the snow damage, since it is easier for layers of snow to pile up on the crowns. Moreover, if breakages occur, more trees are likely to be involved in a "domino effect". Stand density might reduce wind damage as neighbouring trees can provide some shelter to wind, while the intermingling of their roots further increases resistance to wind. However, as regards the effects of stand density, existing literature is inconclusive (Gardiner *et al*., 2010).

The thinning regime employed in a stand is of great importance in terms of stability against these abiotic damages (Cremer *et al*., 1983), since thinning modifies not only the stand density but also the morphological characteristics of the remaining trees, generally increasing their stability. However, the effect of thinning on stand stability is open to debate, as during the first years after a thinning treatment the vulnerability to wind and snow damage increases notably if the remaining trees have not yet attained appropriate allometry to guarantee their stability (h/d, crown length, etc.) (Burschel & Huss, 1987; Valinger *et al*., 2014). This short-term negative effect might be especially important when heavy thinning is applied in a very dense stand or young stand where most of the trees may have a high slenderness coefficient and small crown ratios. This situation was observed after a heavy snowfall in a Scots pine thinning experiment in central Spain which caused greater losses in plots which had been heavily thinned from above five years previously in comparison to unthinned plots (del Río *et al*., 1997). Similarly, greater snow damage after thinning from above has been reported in Sweden (Valinger & Lundquist, 1992). Accordingly, to avoid future damage, it is important to carry out the initial thinning at a young stand age or apply pre-commercial thinning to improve tree stability right from the early development stages (Cameron, 2002). Climate change will lead to less freezing of soils in Nordic countries, so storm damage during winter is expected to increase. Therefore, the forest owners' organization recommends that their members thin stands early and relatively severely to reduce the need for frequent thinning and the likelihood of storm damage at later stages (Keskitalo *et al*., 2016).

Beyond this short-term effect, the thinning intensity and the thinning method strongly influence stand stability. When thinning from below is performed, the trees with highest h/d ratio are removed, and the remaining trees reduce their slenderness coefficient in comparison to unthinned stands due to greater diameter growth, so that the more intensive the thinning, the lower the mean h/d ratio (Fig. 3). As thinning intensity increases, the h/d ratio decreases and the tree taper increases (Montero *et al*., 2000, 2001a; Mäkinen & Isomäki, 2004b; Nilsson *et al*., 2010). The crown height and crown ratio are greater in thinned plots (Varmola *et al*., 2004). Thinning from above might not be suitable for Scots pine stands exposed to heavy storms if suppressed trees are not also extracted, as these trees are more vulnerable and if they fall a "domino" effect can occur (del Río *et al*., 1997). Valinger *et al*. (1994) found similar snow and wind damage expressed as a proportion of basal area between stands thinned from below and from above, although the proportion of trees suffering snow damage was higher in stands thinned from above.

In another Scots pine thinning experiment in Central Spain, the positive long term effect on stand stability of heavy thinning from below was evidenced in the

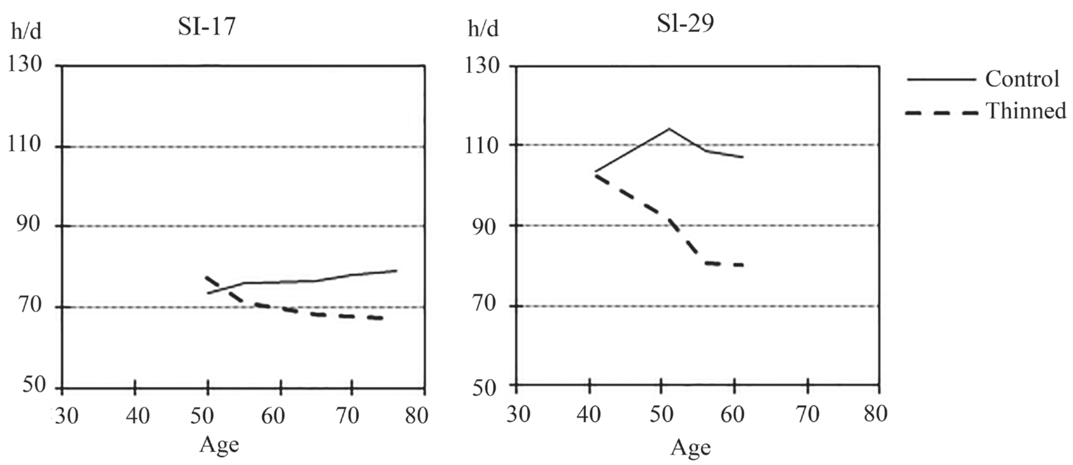

Figure 3. Developement of mean h/d in control and thinned stands (moderate thinning from below) in two experiments with contrasting site fertilities, poor site SI-17 (Covaleda) and rich site SI-29 (Ahedo Pinar) (see description in del Río *et al*., 2008). In control plots mean h/d values increases with age, while the thinning reduce the mean h/d values. At better sites the high mean h/d values in control stand reflect the vulnerability against snow and wind damage.

heavy snowfall of 1996. The damage decreased with the thinning intensity, from 24% of volume damaged in unthinned stands, to 17%, 13% and 6% in light, moderate and heavily thinned stands, respectively (del Río *et al*., 1997). In other studies concerning the effects of thinning on stand stability against snow, similar results were reported for different species (Kramer, 1974; Cremer *et al*., 1983; Schnekenburger *et al*., 1985).

Thinning as an adaptive measure to droughts

Climate change scenarios predict an increase in the intensity and recurrence of droughts. Scots pine is already suffering a process of decline in several parts of its distribution area. This decline is particularly evident in marginal areas of its distribution at lower altitudes and latitudes, mainly as a result of drought stress (Martínez-Vilalta & Piñol, 2002; Dobbertin *et al*., 2005; Bigler *et al*., 2006; Galiano *et al*., 2010; Matías & Jump 2012). Additionally, Scots pine has often been used for afforestation on dry, poor soils in certain European regions (Øyen *et al*., 2006; Sohn *et al*., 2016b), where the effect of severe drought may be more pronounced.

Among the adaptive measures to reduce the vulnerability of forest stands to climate change, the control of stand density through thinning is one of the most important silvilcultural treatments (Spittlehouse & Stewart, 2003). Thinning can improve the growth of the remaining trees by releasing competition for above and belowground resources, including water. After thinning there may be more water availability in soils due to lower interception and water consumption through transpiration as well as more nutrients (*e.g.* Breda *et al*., 1995; Lagergren *et al*., 2008; Gebhardt *et al*., 2014). The positive effect of thinning as regards mitigating the extreme effects of drought has recently been reported for several species, including Scots pine, although the results vary according to species, sites, and thinning regimes (Sohn *et al*., 2016a; Ammer, 2017).

As growth response to thinning depends on the thinning regime, *i.e*. age at the first thinning, intensity, type, and frequency of thinning, the growth response to drought in thinned stands may also depend on these factors (Sohn *et al*., 2016a). In order to better understand the effect of the thinning regime on the impact of drought in Scots pine forests, a recent study analyzed four long-term thinning experiments in Germany with varying site, age at the first thinning, thinning intensity and time elapsed since last thinning (Sohn *et al*., 2016b). They found that in general, thinning significantly improved radial growth recovery after drought events, but scarcely affected the resistance to drought. The effect on growth recovery was greater after the first thinning as well as in recently and heavily thinned stands. However, the time elapsed since the last thinning had the opposite effect on tree resistance, with a negative effect of thinning in the short term and a positive effect about a decade later. This short term effect was attributed to higher evapotranspiration due to wind exposure immediately after the thinning, while the positive effect on recovery was assumed to be due to greater soil water availability.

Other studies dealing with the role of stand density in mitigating the effects of drought on tree growth used approaches based on the effect of competition (Fernández-de-Uña *et al*., 2015; Sánchez-Salguero *et al*., 2015). However, using this kind of approach it is not possible to identify the specific effect of thinning regime characteristics such as those mentioned above, nor the potential effect of thinning on tree growth response to climate. Growth models developed based on two thinning experiments in Scots pine stands in Central Spain predicted less impact of climate under low levels of competition, highlighting the suitability of heavy thinning to mitigate the effects of climate change (Fernández-de-Uña *et al*., 2015).

Intrinsic water use efficiency (WUEi) estimated through stable carbon isotope ratios in tree rings has frequently been used to study the effect of thinning on tree response to drought, although most of the studies found no differences in WUEi between thinned and un-thinned stands (Sohn *et al*., 2016a; Ammer, 2017). A similar result was reported for Scots pine based on data from two thinning experiments in Central Spain, suggesting that in this species also, thinning triggers structural changes to the trees rather than leaf-level efficiency (Fernández-de-Uña *et al*., 2016). Accodingly, Giuggiola *et al*. (2013) found an increase in the leaf area to sapwood area ratio after thinning in a xeric Scots pine forest in Switzerland, associated with lower competition for water. However, at the same site, Giuggiola *et al*. (2016) found differences in the isotopic ratio between thinned and un-thinned stands, indicating less water stress in heavily thinned stands. These contrasting results might be due to species variability, since different responses to drought have been reported among Scots pine provenances (Cregg & Zhang, 2001; Taeger *et al*., 2013). Therefore provenance must be considered when defining thinning schedules to mitigate the impact of drought, although more research into provenance-competition-drought resistance relationships is needed.

It should be noted that climate change (increase in warming and drought events) is projected to reduce growth and survival of Scots pine throughout Europe except for the Northern part (Reich & Oleksyn, 2008), where the growth of Scots pine stands is predicted to increase with climate change due to higher temperatures and a longer growing season. Current management standards may need to be adapted in order to exploit the benefits that climate change seems to provide in the form of increased growth and timber yield under boreal conditions.

Thinning and the provision of ecosystem services

The provision of ecosystem services by forest stands is currently a key aspect when defining management alternatives. The concept of 'Ecosystem services' covers a large number of forest functions, goods and services, which, according to the Millennium Ecosystem Assessment (2005), can be grouped into four categories: supporting, provisioning, regulating and cultural services. Here we review some of the ecosystem services relevant to Scots pine forests for which thinning interventions might have an important impact. We cover some provisioning ecosystem services, such as wood and non-wood forest production; some supporting and regulating services, such as carbon and nutrient cycling, structural diversity; and recreation as a cultural service. As wood yield was covered in the growth and yield section, here we focus on wood quality.

Wood quality

Whereas silviculture only has a minor effect on the quality of wood to be used for paper and fuel, the characteristics of building and construction wood, like strength, stiffness, knottiness, density, distortion, wood heterogeneity and compression wood are highly dependent on thinning (Low, 1964; Pretzsch & Rais, 2016). However, the formation of heartwood seems not to be dependent on the thinning regime (Mörling & Valinger, 1999). The species-specific morphological plasticity and the spatial constellation of the tree within the stand have a specific effect on tree morphology and timber quality. Scots pine belongs to the morphologically highly plastic species with low apical dominance and strong plagiotropic crown extension (Pretzsch & Rais, 2016). Its morphological development and wood quality depends strongly on the spatial constellation within the stands (Agestam *et al*., 1998). Nevertheless, the proportion of large trees with high quality wood at the rotation age also increases with the intensity of the silvicultural schedule (Montero *et al*., 2001b).

When Scots pine is densely surrounded by competitors of similar size, the strong lateral restriction causes slender stems, low knottiness, high wood density, and low distortion of the timber. This pattern of response is widespread in densely established and conservatively managed even-aged pure and mixed stands. As this was the standard silvicultural paradigm in the past, high proportions of timber harvested today display these attributes of quality and allocation pattern. Strong dominance achieved either by vertically overtopping neighbors or by heavy thinning allocates resources to lateral crown extension to improve light interception and to stem growth for mechanical stabilization rather than to height growth (Dippel, 1982; Hynynen, 1995). This results in tapered stem shapes, large-sized knots along the stem axis, as well as lower wood density, eccentric stem cross sections, and crowns with uneven lateral growth. Normally, there is a correlation between stem growth and amount of thick branches but the variation is large (Klang, 2000). In order to counter the tradeoff between high density (improving the quality but slowing down size growth) and low density (reducing the wood quality but accelerating size growth) early tending, crop tree selection, and pruning are common management methods employed (Cameron, 2002; Mäkinen & Isomäki, 2004a; Peltola *et al*., 2002, 2007). Due to the frequent presence of dominant trees with many large branches or 'wolf trees', even at young ages, it is important to remove them through early thinning (Kramer & Jünemann, 1984). Early thinning or pre-commercial thinning can be used for improving quality attributes in young Scots pine stands, and this measure is more effective for increasing stem quality in a stand at later rather than at younger stages (Ruha & Varmola, 1997, Fahlvik *et al*., 2005).

Persson *et al*. (1995) and Blumenrother *et al*. (2001) described the wide variation in wood quality of Scots pine according to provenance, particularly between the apical oriented and straight-growing mountain provenances with high wood quality and the rather more laterally expanding lowland provenances which present a lower quality. However, in the analysis by Person *et al*. (1995), spacing was found to be significant for wood density and fibre length, as well as the interaction provenance-spacing for fiber length and fiber ratio, indicating the importance of controlling stand density for wood quality.

Climate change may be also be a consideration when dealing with wood density, since drought stress can significantly modify stem and wood properties, causing narrower tree rings and higher slenderness values (Mette *et al*., 2015). Furthermore, the increasing incidence of *Viscum album* ssp. *austriacum* is widely assigned to climate change (Dobbertin, 2005; Walentowski *et al*., 2007; Sangüesa-Barreda *et al*., 2013) and means an increasing susceptibility to drought and pathogens as well as a reduction in wood quality (Richter, 2015).

Berries and mushrooms yield

The most common non-wood forest products (NWFP) considered in the management of Scots pine forests are berries and mushrooms, although their abundance and socio-economic relevance varies considerably among regions. Most of the research focusing on the influence of silviculture on berry yield has been developed in Nordic countries, while studies relating silviculture and mushroom yield are more widespread geographically. However, our knowledge is still somewhat limited due to the difficulties involved in studying these NWFP, particularly as the conclusions of many local or regional studies cannot be extrapolated to larger scales. Among other factors, berry and mushroom yields show great spatial and temporal variability, hence the necessity for yield data recorded over long periods and from different sites.

Bilberry (*Vaccinium myrtillus* L.) abundance is closely linked to site conditions (Miina *et al*., 2009), this species being frequently found in many Scots pinewoods. Cowberry (*Vaccinium vitis-idaea* L.) is common in pine forests in northern Europe, particularly at poor sites (Tomé & Faias, 2014). Thinning can affect both the coverage of berry plants as well as berry yield, although there are few studies corroborating this effect in empirical experiments (Hedwall *et al*., 2013). In a Finnish study based on yield measurements over a period of 14 years, it was found that bilberry coverage in Scots pine stands increased with age and basal area until a maximum was reached, while the berry yield depended only on bilberry coverage (Miina *et al*., 2009; Turtiainen *et al*., 2016). As regards basal area, this maximum was around 25 m^2/ha, decreasing with larger basal areas. In a similar study for cowberry, based on 12 year berry yield data, the coverage increased with stand basal area while berry yield decreased with basal area, although obviously the yield also depends on coverage (Turtiainen *et al*., 2013). Using this model, a temporary positive effect of thinning might be expected, probably due to a higher level of light under the tree canopy.

The kind of information available regarding the effect of thinning on mushroom yield is similar to that for berries, with some models relating mushroom yield to stand basal area or density but very few studies focusing on the effect of thinning. Several studies developed in Scots pine forests in Spain have revealed the importance of basal area for mushroom production. Bonet *et al*. (2008) reported a maximum mushroom production in the Central Pyrenees for a basal area around 20 m^2/ha, and found similar results when focusing exclusively on *Lactarius* spp. yield. A similar optimum basal area was found in an updated version of the model by de-Miguel *et al*. (2014). However a larger basal area maximum (around 40 m^2/ha) was reported for *Boletus edulis* in Scots pine stands in Central Spain (Martínez-Peña *et al*., 2012).

Concerning the effect of thinning, Bonet *et al*. (2012) found a positive short term effect on *Lactarius* group *deliciosus yield*, although this study was carried out in *Pinus pinaster* Ait. stands. Salerni & Perini (2004) reported a larger production of *B. edulis* after light thinning than with heavier thinning (20% and 40% of the trees removed) under canopies of different species, including Scots pine stands. Nevertheless, thinning might affect mushroom production since it can produce microclimatic changes in the soil layer which can influence mushroom composition and sporocarp production (Bonet *et al*., 2012).

Carbon and macro nutrient cycling

Nutrient cycling encompasses processes above- and below-ground. In a simplified soil-plant system the allocation of nutrients to foliage, resorption and litterfall production determine the return of nutrients to the soil, whereas litter accumulation, decomposition, rhizodeposition and subsequent immobilization-release patterns control the rate of nutrient inputs. Some of these nutrients, after transformation to plant-usable forms, will be uptaken by plants whereas others will be lost from the forest via leaching or consumption by animals. The balance between nutrient inputs and outputs in the cycle is mediated by abiotic and biotic drivers. The importance of a balanced nutrient budget is that a correct supply of nutrients supports all other ecosystem services (Lavelle *et al*., 2005).

The effects of thinning on nutrient cycling include decreasing litter mass in the forest floor due to reduction of litter production. This effect might be cancelled in the short term due to canopy closure some years after thinning (Roig *et al*., 2005), however long-lasting effects on forest floor have also been observed and if it is accompanied by a reduction in nutrient concentration in green foliage, the nutrient budget may be unbalanced (Jonard *et al*., 2006). Notwithstanding, the type of harvest must also be considered as it will greatly affect the final nutrient stock in the forest floor (Nave *et al*., 2010). Thinning can also modify the abiotic environment needed for correct nutrient cycling in forest ecosystems. In Temperate and Boreal forest ecosystems, the gap opened by thinning allows more radiation to reach the soil, thus increasing the temperature and accelerating the decomposition rate and nutrient concentration in foliage (Thibodeau *et al*., 2000; Vesala *et al*., 2005). This higher soil temperature and subsequent faster decomposition in thinned stands might explain the higher carbon stock found in F and H (fragmented and humus) layers of the forest floor in unthinned stands (Ruiz-Peinado *et al*., 2013). However, in areas where soil moisture is the limiting factor, like in the Mediterranean, the increasing levels of radiation reaching the soil could impair decomposition (Blanco *et al*., 2011; Lado-Monserrat *et al*., 2015; Bravo-Oviedo *et al*., 2017).

Few well-designed studies have been conducted into the impact of thinning on nutrient cycling in Scots pine stands, although two thinning trials in the North of Spain under Mediterranean and Continental-type climate were compared for litterfall production, decomposition and

Table 1. General effects of thinning on growth and yield, stability against wind and snow, response to drought, and ecosystem services according to thinning regime characteristics (empty cells mean lack of significant information regarding these characteristics).

	Target variable	Thinning regime				Effect[a]
		Initial age	Intensity	Method	Rotation	
Growth and yield	Volume growth	Late	Heavy			-
	Mean height		Heavy			0
	Dominant height		Heavy	From below From above		0 +
	Quadratic mean diameter	Early	Heavy			++
	Dominant diameter	Early	Heavy	From above/ Future crop tree From below		++ +
Stability against wind and snow	Resistance to wind	Early Late	Light Heavy	From below	Short	+ -
	Resistance to snow	Early Late	Heavy Heavy	From below From above	Short	+ -
Response to drought	Tree growth recovery		Heavy		Short	+
	Intrinsic water use efficiency					0
Provisioning ecosystem services	Wood quality	Early		Future crop tree		+
	Berries					+
	Mushroom		Light			+
Carbon and nutrient cycle	Litterfall		Heavy			-
	Decomposition					0
	Soil carbon					0
	Carbon stocks		Heavy			-
Biodiversity	Understory vegetation	Early	Heavy		Short	+ -
	Deadwood					0
	Structural diversity		Heavy	From below		-
Recreation	Accessibility/ visibility					+
	Amenity				Short	-

[a] - negative; + positive; 0 neutral or variable depending on other factors.

nutrient flux after thinning (Blanco *et al*., 2005). The results indicated that litterfall production decreased with thinning intensity whereas site climatic descriptors such as soil temperature correlated with litterfall production (Blanco *et al*., 2006). Nutrient return was found to reduce in thinned stands but the effect was greater at the Mediterranean-type site (Blanco *et al*., 2008). Similarly, the reduction in the decomposition rate was also greater at the Mediterranean site (Blanco *et al*., 2011). In this suite of studies, the authors suggested that Scots pines in the Mediterranean region are more sensitive to thinning in the short term. However, another study addressing the long-term impact of thinning on soil condition in a natural Scots pine forest showed that thinned stands, as opposed to unthinned plots, had higher P, K, Mg concentrations in the forest floor and similar carbon and N levels (Bravo-Oviedo *et al*., 2015). The properties of the mineral soil remained unchanged in terms of bulk density and nutrient concentration, although stable stocks of K, Mg and Na throughout the profile in thinned plots would indicate leaching from upper layers. Ruiz-Peinado *et al*. (2016) in a study conducted in a Scots pine afforestation in northern Spain found that thinning had no effect on carbon stocks in either the forest floor or the mineral soil. This pattern has also been observed for different tree species after thinning (*e.g*. Powers *et al*., 2011; Ruiz-Peinado *et al*., 2013).

In the long-term, Ruiz-Peinado *et al*. (2016) observed that with regard to carbon stocks on-site (biomass, deadwood, forest floor and mineral soil) and off-site (biomass removed) after thinning, there were statistical differences in total carbon stocks between unthinned and heavily thinned Scots pine stands. These differences were associated with the amount of total biomass carbon; a loss in biomass production was identified in heavily thinned stands in line with the general pattern observed for volume production. More information regarding the general effects of thinning on carbon sequestration for different tree species is presented in another paper in this issue by Ruiz-Peinado *et al*. (2017).

In northern Europe, soil nutrient sustainability following whole tree harvesting has been the focus of research due to higher demand for fuel wood used in bioenergy. In general, whole tree harvesting during thinning tends to decrease growth more than stem harvesting only, although the effect is slight and soil nutrient and carbon pools do not seem to be notably affected (Helmisaari *et al*., 2011; Tamminen *et al*., 2012).

Biodiversity

Enhancing biodiversity in forest ecosystems is currently one of the main objectives of sustainable forest management. Existing flora and fauna diversity, habitat, structural diversity, etc. should be taken into account in forest planning, and the effects of forestry on biodiversity should also be understood by forest practitioners (Ferris & Pritchard, 2000). Thinning interventions modify stand structure, so they may affect different components of forest ecosystems. Among biodiversity components, the understory vegetation, deadwood, and stand structural diversity are often considered when studying the effects of forest management on biodiversity (Lafond *et al*., 2015).

Thinning results in greater availability of light, water and nutrients to the remaining trees and facilitates the development of an understory layer with a greater number of herbs, shrubs or tree species, mainly comprising early-successional species and aggressive native or non-native taxa. In contrast, repetitive thinning may lead to the appearance of one or just a few dominant understory species or there may be no evident effect when canopy cover pre-thinning is light (Thomas *et al*., 1999; Ares *et al*., 2010). Hence, the impact will depend on thinning intensity and rotation time as well as on pre-thinning species composition. In the case of Scots pine stands in the Nordic countries, a peak in plant species richness is often found in young forest successions. Therefore young stand management (*i.e*. pre-commercial thinning and initial thinning) may promote and sustain this diversity (Widenfalk & Weslien, 2009). For example, some larger gaps could be opened up during the thinning operations to increase plant diversity. Over time there has been a trend towards denser forests in this region, which has led to a decrease in light demanding species and grassland species (Hedwall & Brunet, 2016). Accordingly, in a study involving various forest species in North-Eastern Spain, including Scots pine, Torras & Saura (2008) observed that stand thinning had a positive effect on shrub abundance and on shrub and tree species richness.

Deadwood is a key component in the functioning of forest ecosystems and is both a habitat for fauna and host for decomposer biota. In general, managed stands that have been exploited for timber and firewood contain only a limited amount of deadwood in comparison to unmanaged forests. Thinning operations reduce tree mortality (Mäkinen & Isomäki, 2004a) and existing snags and logs are normally extracted from the forests. The harvesting process produces a small amount of small-diameter deadwood (logging residues) which, in order to reduce the risk of forest fire (mainly in the Mediterranean area) or pest attacks, is chipped and left on the floor or extracted for bioenergy purposes. Although studies focusing on the effects of thinning on amounts of deadwood and decay processes are lacking, various modelling studies have been carried out to

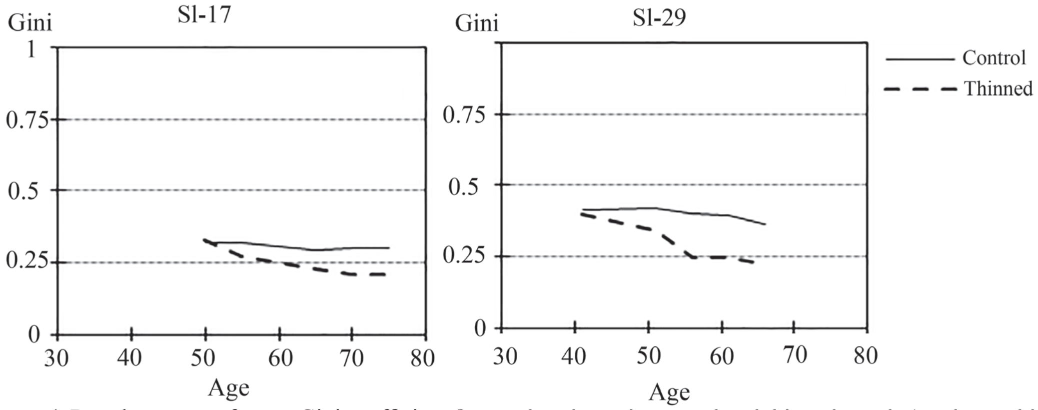

Figure 4. Developement of mean Gini coefficient for tree basal area in control and thinned stands (moderate thinning from below) in two experiments with contrasting site fertilities, poor site SI-17 (Covaleda) and rich site SI-29 (Ahedo Pinar) (see description in del Río *et al.*, 2008). In control plots the Gini coefficient remains constant with age, while the low thinning reduces this coefficient indicating higher homogeneity of sizes. The Gini coefficient reflects higher inequality in sizes at the richer site than at the poor site in control plots.

estimate coarse woody debris in Scots pine forests (*e.g.* Rouvinen *et al.*, 2002; Montes & Cañellas, 2006; Herrero *et al.*, 2010).

Structural diversity of stands is often used as an indicator of biodiversity (McElhinny *et al.*, 2005; Alonso *et al.*, 2016), although more complex structures do not necessarily mean higher diversity (Hunter, 1999). Thinning alters the structural diversity by reducing stand density along with the selective removal of trees from specific social classes, depending on the thinning method employed. Some studies concerned with thinning trials in Scots pine stands have reported that thinning from below reduced the coefficient of variation of the diameter distribution; this distribution being more skewed to the right and with higher kurtosis (Montero *et al.*, 2000; Mäkinen & Isomäki, 2004b; Crecente *et al.*, 2009). This greater homogeneity of tree size can also be expressed through the Gini coefficient (de Camino, 1976), with lower values in thinned stands (Fig. 4). Thinning from below may also reduce the range and standard deviation of tree heights (Barbeito *et al.*, 2009).

Recreation

Although public preferences for different types of forest may change over time (for educational reasons among others), many people consider unmanaged forests or old-growth forests to be unsuitable for recreation (Lindhagen & Hörnsten 2000). Managed forests, which are generally more open and have more light, may be preferable for recreation (Hale *et al.*, 2009). Thus, the forest management adopted must also consider recreational use, for example, by creating larger gaps and thinning the understory to create better views inside the forests (Jankovska *et al.*, 2014). Thinning treatments can enhance preferences for recreation by facilitating accessibility and maintaining intermediate stand densities (Jensen & Skovsgaard, 2009). Longer rotations are also preferable since harvesting and clear-cutting are often looked upon as disturbances that hinder recreation (Holgen *et al.*, 2000). These studies provide a general picture of recreational preferences in all types of forest. However, specific studies focusing on thinned Scots pine stands are required. For example, in Scots pine stands it may be less important to open up gaps in the forest to improve views or provide amenities than in darker spruce or fir stands.

Challenges

Studies addressing the effects of thinning on Scots pine stands began more than a century ago (Assmann, 1970), therefore abundant information is available on growth response to thinning. Traditional thinning experiments were originally designed to study growth and yield principles, but today provide an important source of information to satisfy the current demand for knowledge about aspects such as the effect of thinning on carbon sequestration, structural diversity, or growth response to extreme droughts (*e.g.* Crecente *et al.*, 2009; Bravo-Oviedo *et al.*, 2015; Ruiz-Peinado *et al.*, 2016; Sohn *et al.*, 2016b). The main effects of thinning on the different aspects compiled in this review are summarized in Table 1. However, our review highlights the fact that several important questions still need to be addressed, particularly those issues which were not initially considered among the objectives of the trials and which cannot be studied through retrospective analysis, such as the effects of thinning on non-wood forest products, which would require further thinning studies.

As mentioned previously, the effects of thinning on growth and yield have been extensively studied in various regions throughout the distribution area of Scots pine. Although the main species growth responses to thinning are well documented, there are still some uncertainties which require further research. The density-growth relationship for Scots pine is influenced by site conditions and varies among regions. This means that the expected climate change scenario, which may have positive or negative effects on growth depending on the region, would modify this relationship. Furthermore, thinning can improve height growth at poor, dry sites, which will become more prevalent as a consequence of climate change. These aspects must be considered when adapting silvicultural guidelines to climate change. Similarly, many Scots pine sites in Central Europe have been enhanced considerably through deposition, regeneration of soil after depletion and litter raking. Hence, thinning prescriptions should also be adapted accordingly.

Most of our current knowledge with regard to the effects of thinning on growth and yield is based on concepts influenced by the prevailing views in forest practice (Nilsson *et al*., 2010). For the main part, this means selection from below with the aim of promoting tree size growth, with only a small reduction in yield. In order to more effectively encourage size growth in selected trees, selective thinning and future crop tree thinning (Z-tree concept) have become common concepts over recent decades (Abetz, 1974; Utschig *et al*., 2011). Experiments conducted in accordance with these concepts are rare and in any case are still at too early stage to draw any general conclusions, although a severe reduction in stand growth after heavy selective thinning from above has been identified (Fig. 1). This finding must be tested over a longer period.

Our review of the effects of thinning on other ecosystem services apart from wood provision revealed the scarce number of studies undertaken to date, especially as regards biodiversity and social functions. Future thinning studies should not only focus on these functions and services in order to increase our understanding of them, but should also include a large number of ecosystem services to enable us to analyse the trade-offs among them. Forest management cannot be expected to maximise all the services at the same time, so it is crucial to identify the main trade-offs (Wang & Fu, 2013; Alonso-Ponce *et al*., 2016). Besides the typical trade-offs between wood yield and wood quality, thinning can involve other trade-offs such as those between wood quality and structural diversity or carbon sequestration, which need to be addressed. In the same way, trade-offs between adaptation to and mitigation of climate change are especially important for thinning interventions. In order to adapt Scots pine stands to a higher frequency and severity of droughts (predicted for many regions) the intensity of thinning must be heavy, even though this would reduce the carbon fixing capacity of the stand.

In many areas where Scots pine grows, the management objectives have changed from monoculture plantations towards 'closer to nature' forestry, with greater importance given to multifunctionality. In this context, admixed species are often promoted because of the expected improvement in the provision of ecosystem services and greater stability (Pretzsch *et al*., 2015, 2016; del Río *et al*., 2017). Depending on the admixed species, a release of the pines by cutting away neighbors of more competitive species such as beech or spruce might be necessary. However, thinning experiments in mixed Scots pine stands are currently scarce (Primicia *et al*., 2016).

The establishment and long term maintenance of sound thinning trials is costly in economic terms as well as demanding on human resources and time, with many difficulties inherent to the 'long term' character of such trials. Frequent changes can occur as regards the people involved, funding possibilities or research interests. Additionally, damage caused by biotic and abiotic disturbances can destroy the initial experimental design (Mäkinen & Isömaki, 2004a). Studies comparing thinning schedules may necessarily involve large experiments given the high number of possible alternatives as regards initial age of thinning, thinning method, intensity and rotation period (Nilsson *et al*., 2010). However, such experiments provide the best means to test the long term effects of thinning on different ecosystem services. The results from long term thinning trials provided in this review highlight the importance of maintaining long term experimental plots, which contribute in a unique way to forest ecosystem monitoring (Pretzsch *et al*., 2014). In order to maintain a sustainable data and knowledge base for science, training, and demonstration purposes, we need new thinning experiments which cover a broad range of ecosystem services under different site conditions, as Scots pine growth is very site-sensitive.

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